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ANALYSIS REPORT
2302-02-04001

REVISION	1.0
DATE	18.10.2024

VERIFICATION OF GRØFT DESIGN WITH TB 880

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EXECUITVE SUMMARY

In this report the software Grøft Design® (GRØFT) was validated with reference to the Technical Brochure 880 [1] issued by CIGRE Working Group B1.56 (TB 880). The purpose of the validation is to ensure that the current ratings in the software are computed consistently and in accordance with IEC 60287 (IEC)[1] standard. The software is benchmarked with 6 reference case studies (CS0, CS1, CS4, CS 5, CS9, CS10), for which a description of the modeling technique and guidelines for users of GRØFT are provided.

GRØFT can reproduces the results found in TB 880 for selected study cases with a high accuracy. The software provides an intuitive and decision supporting interface that facilitates setting up the reference conditions for cable rating calculations. Because GRØFT utilizes FEM (finite element method) calculations, it is much more flexible to set up the geometrical parameters and boundary conditions in comparison to the IEC standard. Furthermore, GRØFT has a built-in library of standardized and modern cables with the possibility of modifications and setting up user-defined components and properties. Users seeking current rating analysis of standardized distribution cables may easily set up a calculation model consistent with the IEC. Engineers are free to introduce several geometrical adjustments, both for cables and trenches, far beyond the scope of the IEC standards. Analysis of trenches with multiple cable arrangements and tailor-made layouts are possible as well. The cable designer supports the Milliken conductor.

The software does not yet support the analysis of cables with steel armor, therefore the subsea cables found in TB 880 were excluded from the analysis.

It must be noted that the user of the Grøft Design® software should have some understanding in the field of cable rating calculation. The final assessment of the cable rating should be made by qualified personnel. The results that are obtained in GRØFT depend on several cable parameters, factors and to a large extent, upon the thermal parameters of the environment in which cables are laid.

[1] 60287-1-1 [9] (IEC1) and IEC 60287-2-1 [2] (IEC2)

IEC 60287 AND TB 880

International standard IEC 60287 introduces a widely accepted formulae- and parameter-based method for current rating calculations of power cables. It is used as a basis by engineers performing the calculations and by parties requesting the compliance of calculations with acknowledged references. The standard is, however, restricted to the limited number of cable types and their installation. Furthermore, setting up a theoretical model of cable requires expertise in the field of cable rating calculations. Even highly qualified engineers with the support of computer aided analysis tools may be not able to utilize the theoretical basis found in the standard to analyze complex cable installation and represent correctly the numerous design features found in the modern cable design. This may lead to misconceptions in cable rating analysis, resulting in over- or underrating of cable installation.

In order to respond to the need for more comprehensive and straightforward solutions for calculation of the cable rating, CIGRE Working Group B1.56 has issued a Technical Brochure (TB 880) that supplements the IEC standard with extended study cases for analyzing modern and more complex cable installation. The brochure comprises of several case studies of cables and provides an elaborative guideline for engineers performing a theory-based cable rating calculation. Furthermore, TB 880 is used as the verification reference for commercial software for cable rating calculation.

GRØFT DESIGN

REN AS has developed software Grøft Design® (GRØFT) that offers user-oriented interface for analysis of the current rating of cables in trenches. The program is built on the COMSOL Multiphysics® - a simulation software based on Finite Element Method (FEM). The advantage of the use of GRØFT is the structured and automatized design process of cable systems without knowledge of FEM.

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1. METHOD

In order to evaluate the performance and the accuracy of GRØFT with reference to TB 880, all case studies enclosed in TB 880, for which the boundary conditions are supported by functionalities found in GRØFT, are analyzed. The comparison of the resulting temperatures and heat losses is made for the reference cable rating. Cables are modelled in GRØFT according to the specifications found in TB 880. All similarities and variations related to the modelling techniques of cable and establishment of reference conditions are distinguished. The discrepancies in results of cable rating between GRØFT and TB 880, are discussed in detail. For several cases the argumentation is done with the help of hand-on calculation based on IEC and empirical models representing the heat transfer components. The details of the analytical models are enclosed in this report.

The notation and units presented in this report correspond to the IEC standard.

2. BOUNDARY CONDITIONS

For all cases, except for cable in trough, the cable installation (*installation depth*) is placed 1 m beneath the ground surface. The installation depth (not the *Layout depth,* as found in GRØFT) is measured from the center of the cable for flat laying of cables, and from geometrical center of the cable's installation for triangular formation, i.e. cables or ducts. In GRØFT this distance (*installation depth*) is not directly represented with the parameter, therefore it must be adjusted accordingly. For cables in touching trefoil or cables placed in touching pipes, the parameter *Cover thickness*, shall be calculated as:

$$Cover\ Thickness = \ installation\ depth - \left(\frac{1}{2} + \frac{\sqrt{3}}{3}\right) \cdot cable\ or\ pipe\ diameter$$

For cables in flat formation:

$$Cover\ Thickness = \ installation\ depth - \frac{1}{2} \cdot cable\ or\ pipe\ diameter$$

For all cases, except for cable in trough, the ground surface is assumed to be isotherm with a temperature of 20°C.

The bonding type for cables varies for each case.

3. HEAT LOSS IN CABLE

The analysis that are performed in GRØFT consider all types of heat losses, i.e. conductor, sheath and dielectric losses. IEC distinguishes the circulating current losses in sheath from eddy current losses, therefore it is possible to exclude one of these, depending on cable and bonding design. In the analytical model of TB 880 for solid bonded cables, both these losses are considered for all case studies, therefore in terms of sheath losses, GRØFT and TB 880 are consistent. GRØFT supports the single-point bonding as well, for which the circulating current losses are excluded.

4. FOR GRØFT USERS

All cable models and case studies analyzed in this report are available in the software documentation. For users that compares their results with the one found in TB880 and GRØFT, it must be emphasized that the change of the little detail of cable model mays result in considerable change of its ampacity. Therefore, the model of each case study found in GRØFT was modelled so that it represents most accurately the recommendations made by the experts of CIGRE WG B1.56.

For any case study, beyond the scope of this report, the users of GRØFT must be aware of the importance of the establishing boundary conditions and the design decision they make. GRØFT support most of the standard cables design with the straightforward modelling interface, however, the amount and variability of parameters may lead to misconceptions. This in turn results in over- or underrating the cable carrying capacity. In case of any modelling uncertainties, users are encouraged to contact the technical support of the software.

5. INTRODUCTORY CASE STUDY 0

The introductory cases #0-1,2,3 and 5 found in TB 880 are modelled and simulated in GRØFT (see Figure 5.1). A copper 132 kV 630 R cable is analyzed for all basic configurations, except of cables laid in free air and directly exposed to solar radiation (case #0-4), as GRØFT does not provides this functionality yet. The comparison of the resulting cable rating between TB880 and GRØFT is documented.

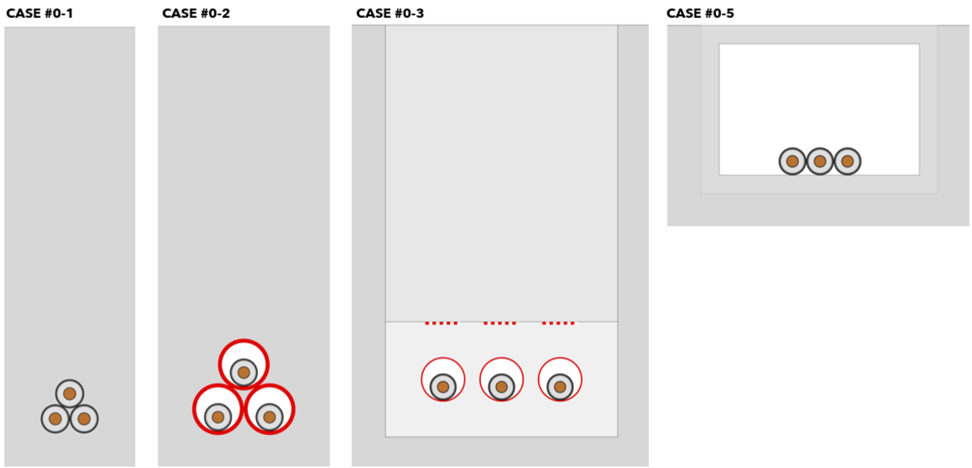

FIGURE 5.1 GEOMETRICAL REPRESENTATION OF CASE #0-1, 2, 3 AND 5

5.1 CASE#0-1: DIRECTLY BURIED CABLES IN TREFOIL

For the analyzed 132 kV cable, the ampacity calculated in GRØFT is close to the found in TB 880 (see Table 5.1). The difference of 0.65% is marginal. Opposite to the IEC model, in the GRØFT model the conductivity of the metallic components is modelled, hence, the effect of the circumferential heat conduction of metallic layer for trefoil formation is considered. Therefore, for cables in a close proximity, the increasing cross section of metallic sheath leads to deviations between analytical and FEM model. This is discussed further in section 8 of this report.

Furthermore, according to the TB 880, that follows the IEC approach for the calculation of the thermal resistances T_4 for cables in touching trefoil, the factor $f_\varphi = 1.6$ is used to multiply the thermal resistance of jacket T_3. This factor can be calculated as follows [2]:

$$f_\varphi = \frac{\pi}{\pi-\varphi} = 1.298 \qquad (5.1)$$

$$\varphi = \frac{\pi}{6} + \frac{D_e}{\sqrt{D_e^2+\frac{d_c^2}{4}}} \qquad (5.2)$$

Where:

d_c - Conductor diameter

D_e - Cable diameter

As the factor f_φ, that correspond the exact geometrical parameters of the cable, is applied instead for the analytical model of IEC, the results are comparable with the FEM model with a very high accuracy.

Cable		XLPE copper 132 kV 630R (Al) CASE #0-1				
Configuration		Trefoil, solid bonded				
Parameter		Symbol	Unit	TB 880	TB 880 + $f_{\varphi} = 1.298$	GRØFT
$I = 803.16\ A$	Loss conductor	Wc	W/m	25.49	25.45	25.30
	Loss Screen	Ws	W/m	9.34	9.35	8.65
	Dielectric loss of insulation	Wd	W/m	0.385	0.385	0.385
	Max temperature of conductor	T_{max}	°C	90.00	89.36	89.00
Permissible current rating/ampacity		I	A	**803.16**	**806.53**	**808.4**

TABEL 5.1 COMPARION OF RESULTS BETWEEN TB880 AND GRØFT FOR CASE #0-1

5.2 CASE#0-2: CABLES IN TOUCHING HDPE DUCTS

A considerable difference in calculated current rating of 15 A was found between the GRØFT and TB 880 model (see Table 5.2, TB 880 and GRØFT[3]). This is due to the different approach for modelling of air resistance in pipes. TB 880 model implements the approximation of air resistance based on IEC2. Furthermore, in the IEC2 model, cables are placed in the center of pipes. In GRØFT, the conductive, convective and radiative heat transfer are simulated with FEM. Moreover, cables are placed on the bottom of the pipes, as this represents the realistic arrangement. Hence, the heat dissipates from cables through pipes, and to the surrounding, to a greater extent by means of conduction than in TB 880 model.

GRØFT utilizes the IEC2 approach (IEC air) for calculation of air resistance in pipes as well, as the cables are placed in the center of pipes. This functionality is not the default setup; therefore, it must be switched on by the user. The difference in resulting temperature of cable, between the reference TB 880 model and GRØFT, is of 2.8 °C in that case. These models should be consistent, as the same reference conditions were established. On the other hand, as it will be presented in the case #0-3, GRØFT implementing the IEC air is much closer to the results based on IEC2 found in TB 880, as the distance between pipes increases.

IEC, which TB 880 refers to (point 4.7.2.3 of TB880), specifies that for the touching HDPE pipes the external resistance of the duct, i.e. soil, shall be treated as for cables in trefoil formation to consider the distorted temperature of the circumference of cable serving that is not an isotherm, as seen in Figure 6.2. The distribution of the temperature is clearly distorted, both for the air volume and the pipe. On the other hand, the temperature of the conductor is not equal for each phase as it is for the trefoil formation, therefore the mutual heating does not correspond the trefoil formation for that case.

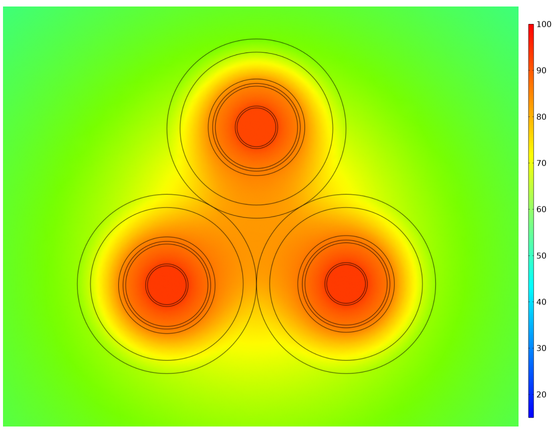

FIGURE 5.2 DISTRIBUTION PLOT OF TEMPERATURE [°C] FOR CASE #0-2 – GRØFT WITH IEC AIR

Although GRØFT model implementing the IEC air seems to represent adequately the physics of heat transfer in the air layer in pipe defined in IEC, it must be pointed out that the IEC model is a quite rough estimation. Thermal resistance of the air layer is calculated barely as a function of temperature in pipe and cable diameter. The heat transfer between the surfaces of cable and pipe is, however, much more complex and the diameter of the pipe shall be taken into consideration as well. The constants U, V, Y [2] that define the thermal resistance of the air in the pipe, are a good representation for most of the general cases for power rating calculations, however the accuracy of this approach might be questioned. Therefore, in order to verify whether the heat transfer simulated in GRØFT is accurate with regards to realistic conditions, the air in the pipe was modelled with the empirical model that describes the natural convection and radiative heat transfer between concentric cylinders [1] (see Appendix 1 for model description). This model confirms that the heat transfer by means of the natural convection and radiation simulated in GRØFT is in line with the theoretical approximations.

Whit such evidence, the conclusion is made, that the temperatures of cables placed in pipes, calculated in GRØFT, gives more accurate results in comparison to the IEC method presented in TB 880. Furthermore, for the GRØFT model that implements the convective heat transfer with the empirical model developed by SINTEF [3], the highest accuracy is found. The difference between the IEC approach and GRØFT model for that case is 3.3°C.

	Cable	**XLPE copper 132 kV 630R (Al) CASE #0-2**							
	Configuration	**Triangular in HDPE pipes, solid bonded**							
Parameter		**Symbol**	**Unit**	**TB 880**	**GRØFT+IEC air**	**GRØFT[1,4,5]**	**COMSOL[2,5]**	**GRØFT[3,5]**	**GRØFT[4,5]**
$I = 679.84\ A$	Loss conductor	Wc	W/m	17.85	17.90	18.79	18.10	18.00	18.65
	Loss Screen	Ws	W/m	15.22	15.04	14.95	14.91	14.89	14.92
	Dielectric loss of insulation	Wd	W/m	0.385	0.385	0.385	0.385	0.385	0.385
	Max temperature of conductor	T_{max}	°C	90.00	92.800	96.70	96.50	93.300	94.60[6]
Permissible current rating/ampacity		I	A	**679.84**	**666.4**	-	-	**663.8**	**658.3**

[1] Cables placed in the center of the pipe
[2] Empirical model for heat transfer between two concentric cylinders implemented in COMSOL, that correspond model GRØFT[1,4,5]
[3] Cables placed in the bottom of pipe, the SINTEF [3] model for convection in pipe is applied
[4] Model with simulated natural convection
[5] The emissivity of cable serving, and pipe is set by default to 0.8 in GRØFT. IEC does not specify this parameter.
[6] These results are conservative with regards to the model that implements the SINTEF model for convection. This is due to the rough quality of the mesh and the fact that the cable does not touch pipes in the GRØFT model. For much better quality of mesh and cables touching the pipes, the temperature is 93.04 °C. This simulation was done in COMSOL. However, in GRØFT the quality of mesh is sufficient to give the results with a high precision. With the improvement of the mesh, the nonlinearity of the computational model increases, and the time required for the solver to find a solution is extended considerably.

TABEL 5.2 COMPARION OF RESULTS BETWEEN TB880 AND GRØFT FOR CASE #0-2

	Cable	**XLPE copper 132 kV 630R (Al) CASE #0-3**							
	Configuration	**Flat formation, solid bonded**							
Parameter		**Symbol**	**Unit**	**TB 880**	**GRØFT + IEC air**	**GRØFT[2,6]**	**COMSOL[3,6]**	**GRØFT[4,6]**	**GRØFT[5,6]**
$I = 633.04\ A$	Loss conductor[1]	Wc	W/m	15.48 15.25 15.14	15.40 15.30 15.10	16.10 15.9 15.8	15.51 15.36 15.23	15.30 15.20 15.10	16.0 15.8 15.7
	Loss Screen[1]	Ws	W/m	26.35 12.12 19.89	27.23 12.20 18.66	27.15 12.08 18.83	27.00 12.06 18.52	27.21 12.19 18.75	27.31 12.19 18.82
	Dielectric loss of insulation	Wd	W/m	0.385	0.385	0.385	0.385	0.385	0.385
	Max temperature of conductor	T_{max}	°C	90.00	88.80	93.50	93.21	89.10	89.50
Permissible current rating/ampacity		I	A	**633.04**	**638.7**	-	-	**637.3**	**643.5**

[1] Heat loss accordingly L3, L1 and L2
[2] Full FEM model with simulated natural convection, cables placed in the center of pipe
[3] Empirical model for two concentric cylinders corresponding to GRØFT[2] model
[4] Empirical model introduced by SINTEF [3]
[5] Full FEM model with simulated natural convection
[6] The emissivity of cable serving, and pipe is set by default to 0.8 in GRØFT. IEC does not specify this parameter.

TABEL 5.3 COMPARION OF RESULTS BETWEEN TB880 AND GRØFT FOR CASE #0-3

5.3 CASE#0-3: CABLES IN PVC DUCT EMBEDDED IN COCRETE IN FLAT FORMATION

The current rating of the 132 kV cable for case #0-3 calculated with GRØFT is slightly higher than the one defined in TB 880, that is presented in Table 5.3 (TB 880 and GRØFT[4,6]). This is due to the fact, that cables in the GRØFT model are placed on the bottom of the pipe, that works in favor of heat dissipation. For this case, GRØFT simulations were validated with the empirical model describing heat transfer by the natural convection and radiation between concentric cylinders (GRØFT[2,6] and COMSOL[3,6]).

5.4 CASE#0-5: CABLES IN TOUCHING FLAT FORMATION IN AN UNFILLED TROUGH

This study case examines the cable installation in touching flat formation placed in trough. Calculation performed in TB 880 utilizes the analytical model describing the cables placed in the free air, found in IEC. No details that describe the reference conditions based on which the mathematical model by IEC was developed are given. The ambient temperature of the air is set to 25 °C, and during the analysis, is successively increased due to the heat that is dissipated from cable to the enclosure of trough.

An attempt was made to reflect these conditions in GRØFT. Cables were placed in the middle of the trough's height and moved toward the wall. This represents "open air conditions" described in IEC2. The emissivity of cable serving and trough is set by default to 0.8 in GRØFT. This parameter is not specified in the IEC models. The ground surface does not behave as an isotherm, i.e. its temperature is established based on varying temperature of the top surface of trough that dissipates heat to the open air with reference temperature of 25 °C. The thermal resistivity of surrounding masses is set to 3.5 m.K/W, as this might correspond to the realistic setup near the substations where trough tends to be installed.

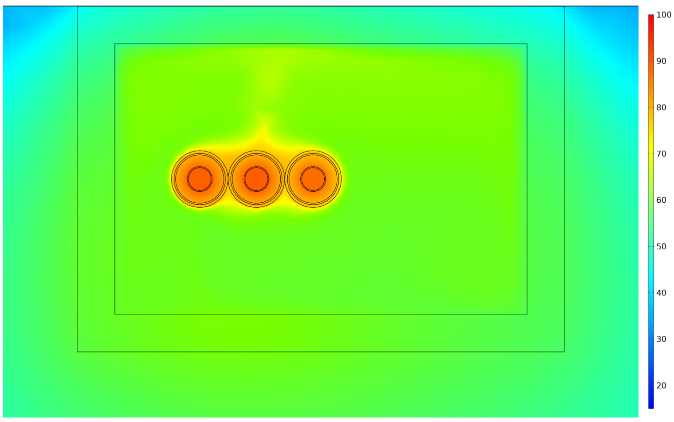

FIGURE 5.3 DISTRIBUTION PLOT OF TEMPERATURE [°C] FOR CASE #0-5

Assuming the aforementioned conditions, the comparable results were obtained in GRØFT with reference to TB 880 analysis. The ampacity is higher by 1.23% for the GRØFT model. The description of the reference conditions for case #0-5 is, however, not sufficient to compares GRØFT and TB 880. The reference conditions set in the GRØFT model are a guess of the author of this report. The GRØFT model that simulates the heat transfer in trough by means of natural convection, was validated with the empirical mode instead. This is done in order to argue for that the heat transfer in GRØFT reflects the expected, realistic conditions.

	Cable	**XLPE copper 132 kV 630R (Al) CASE #0-5**			
	Configuration	**Touching flat formation, solid bonded**			
Parameter		**Symbol**	**Unit**	**TB 880**	**GRØFT**
$I = 754.86\ A$	Loss conductor	Wc	W/m	22.52	22.7
	Loss Screen	Ws	W/m	18.37	18.38
	Dielectric loss of insulation	Wd	W/m	0.385	0.385
	Max temperature of conductor	T_{max}	°C	90.00	88.4
	Increase of the temperature in trough above reference ambient temperature of 25 °C	$\Delta\theta_{tr}$	°C	28.35	34.29
Permissible current rating/ampacity		I	A	**754.86**	**764.2**

[1] Heat loss related to L3 (on the left side)

TABEL 5.4 COMPARION OF RESULTS BETWEEN TB880 AND GRØFT FOR CASE #0-5

5.5 CASE#0-5: VALIDATION OF GRØFT WITH EMPIRICAL MODEL

Case #0-5 with modified boundary conditions is built in GRØFT, as presented in Figure 5.4. Cable installation is placed on the bottom surface of the trough. The ground surface is an isotherm with temperature set to 25 °C. The heat transfer is simulated by means of natural convection, conduction and radiation.

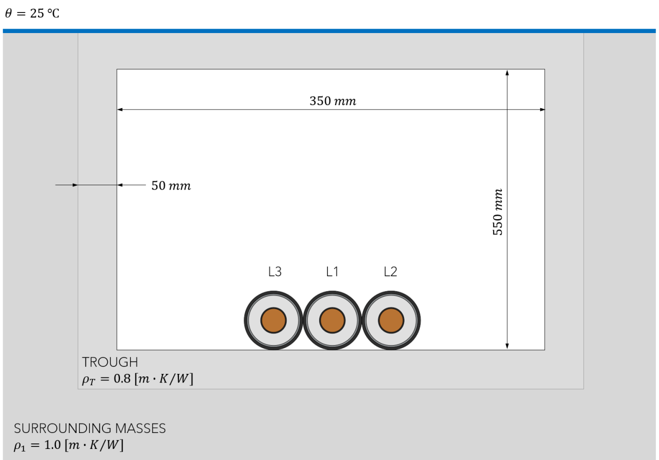

FIGURE 5.4 REFERENCE GEOMETRY OF THE GRØFT MODEL USED FOR COMPARISON WITH EMPIRICAL MODEL

A similar model is built in software COMSOL Multiphysics®, as presented in Figure 5.5. The natural convection in trough is represented with the analytical model described by Hollands et al. [5] that estimates the effective conductivity of air k_{eff} in horizontal enclosures based on the temperature difference $\theta_1 - \theta_2$, accordingly, of the bottom and top surface of trough. The temperature θ_1 is the average temperature of the bottom surface of the trough and the cable surface (marked with red line in Figure 6.5), that are exposed directly to the air volume in which the natural convection is considered. Furthermore, the heat rate Q_{nc} that describes the amount of heat that would be dissipated from cable surface placed in open air, is applied along the curve determined with the circumference of the cable installation, marked with green line in Figure 5.5. The heat rate Q_{nc} is determined with the theoretical expression [5] describing the natural convection for horizontal plate facing upward (top surface of cable with temperature $Q_{c(up)}$) and downward (bottom surface of cable with temperature $Q_{c(down)}$). The application of Q_{nc} is disregarded for the air gaps between cables determined by the bottom surfaces of the cables. In this model, the heat transfer is considered only with the calibrated conductive, i.e. k_{eff}, and the radiative components. The description of the analytical model is found in Appendix 2.

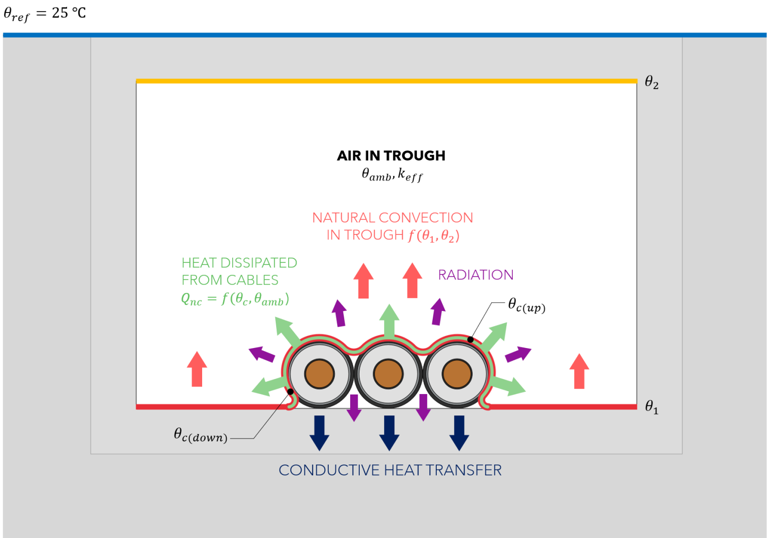

FIGURE 5.5 COMSOL MODEL IMPLEMENTING THE ANALYTICAL EXPRESSION DESCRIBING THE HEAT TRANSFER BY MEANS OF NATURAL CONVECTION IN TROUGH – SEE APPENDIX 2 FOR MODEL DESCRIPTION

The comparison of resulting maximum temperature of conductor, between COMSOL and GRØFT model, is performed for varying cable loading. The analysis results are presented in Figure 5.6. GRØFT model correlates well with the theoretical approximation.

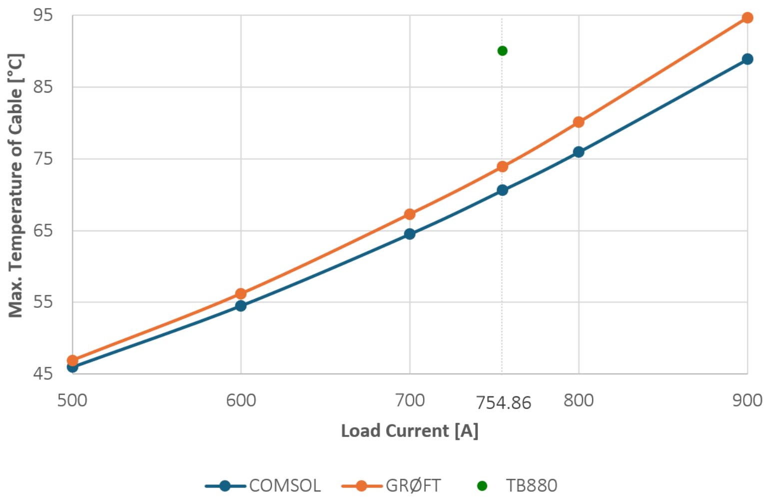

FIGURE 5.6 COMPARISON OF GRØFT MODEL SIMULATING THE HEAT TRANSFER BY MENAS OF NATURAL CONVECTION AND COMSOL MODEL IMPLEMENTING THEORETICAL APPROXIMATION

The importance of establishing the boundary conditions for such cable installation is evident as this analysis is compared with the TB 880 results. GRØFT was found a tool that represents accurately the heat transfer by means of natural convection in enclosures. The calculations performed in GRØFT in that case is however nonlinear and the solution is not guaranteed, especially for complex cable arrangement. In that case, GRØFT users are encouraged to contact the software support.

6. CASE STUDY 1 – 132 KV CABLE

For the analyzed XLPE 76/132 kV cable, the ampacity calculated in GRØFT is similar as in TB 880 (see Table 6.1).

	Cable	**XLPE 76/132kV 1x1200 mm2 copper CASE 1**			
	Configuration	**Trefoil, solid bonded**			
Parameter		**Symbol**	**Unit**	**TB 880**	**GRØFT**
$I = 990.54\ A$	Loss conductor	Wc	W/m	21.73	21.73
	Loss Screen	Ws	W/m	17.18	17.09
	Dielectric loss of insulation	Wd	W/m	0.465	0.465
	Max temperature of conductor	T_{max}	°C	90.00	90.600
Permissible current rating/ampacity		I	A	**990.54**	**986.5**

TABEL 6.1 COMPARION OF RESULTS BETWEEN TB880 AND GRØFT FOR CASE 1

7. CASE STUDY 4 – 33 KV LAND CABLE

The ampacity for the 33 kV cable has been calculated with high accuracy with regards to TB 880 (see Table 7.1).

	Cable	**33kV land cable, CASE 4**				
	Configuration	**Trefoil, solid bonded**				
Parameter		**Symbol**	**Unit**	**TB 880**	**GRØFT**	**GRØFT[1]**
$I = 537.45\ A$	Loss conductor	Wc	W/m	28.20	28.1	28.3
	Loss Screen	Ws	W/m	1.23	1.48	1.48
	Dielectric loss of insulation	Wd	W/m	0.108	0.108	0.108
	Max temperature of conductor	T_{max}	°C	90.00	89.8	91.2
Permissible current rating/ampacity		I	A	**537.45**	**538.1**	**533.7**

[1] Model of cable with modified thermal resistance T_1 of layer between conductor and screen according to IEC ($1.07 \cdot T_1$)
Modified thermal resistivities:

- conductor screen $\rho_{cs} = 2.675\ [W/m.K]$
- insulation $\rho_{cs} = 3.745\ [W/m.K]$
- insulation screen $\rho_{cs} = 2.675\ [W/m.K]$
- semiconducting bedding $\rho_{cs} = 6.42\ [W/m.K]$

TABEL 7.1 COMPARION OF RESULTS BETWEEN TB880 AND GRØFT FOR CASE 4

However, in GRØFT, the screen is modelled as uniform layer. The cable design introduces the copper wires that are distributed on less than 50% of the circumference of layer over the insulation. According to IEC, for cables in trefoil formation, the assumption that the screen is an isotherm is no longer valid, i.e. the spacings between wires disturb the uniform heat distribution. Therefore, the thermal resistance of layer between cable core and screen T_1 shall be multiplied by the factor 1.07. This contributes to the slight derating of such cable, as seen when comparing GRØFT and GRØFT[1] model of cables (see Table 7.1).

As the 33 kV land cable has a screen composed of wires, in the TB 880 calculations, the eddy current losses are disregarded. In the GRØFT model, as a consequence of representing the screen as uniform layer, these losses are included.

8. CASE STUDY 5 – 400 KV LPOF CABLE

With regards to TB 880, the considerable current rating difference calculated in GRØFT is reported for the analyzed 400 kV LPOF cable (see Table 8.1). However, as presented in Table 8.2, for cables in flat formation, single point bonded, ampacity calculated in GRØFT is close to the calculations performed in TB 880.

	Cable	400kV LPOF			
	Configuration	**Trefoil, solid bonded**			
Parameter		**Symbol**	**Unit**	**TB 880**	**GRØFT**
$I = 903.62\ A$	Loss conductor	Wc	W/m	10.66	10.50
	Loss Screen	Ws	W/m	22.56	18.24
	Dielectric loss of insulation	Wd	W/m	5.950	5.950
	Max temperature of conductor	T_{max}	°C	85.00	78.30
Permissible current rating/ampacity		I	A	**903.62**	**958.2**

TABEL 8.1 COMPARION OF RESULTS BETWEEN TB880 AND GRØFT FOR CASE 5 – CABLES IN TREFOIL

	Cable	400kV LPOF			
	Configuration	**Flat, single point bonded/cross-bonded**			
Parameter		**Symbol**	**Unit**	**TB 880**	**GRØFT**
$I = 1590.2\ A$	Loss conductor[1]	Wc	W/m	31.85	31.8
	Loss Screen[1]	Ws	W/m	3.73	3.7
	Dielectric loss of insulation	Wd	W/m	5.950	5.950
	Max temperature of conductor	T_{max}	°C	85.00	84.4
Permissible current rating/ampacity		I	A	**1590.2**	**1596.7**
[1] Heat loss related to L1 (middle phase)					

TABEL 8.2 COMPARION OF RESULTS BETWEEN TB880 AND GRØFT FOR CASE 5 – CABLES IN FLAT CONFIGURATION

For case study of the 400 kV cable in trefoil presented in TB 880, the induced circulating current are much higher than these calculated in GRØFT. This is not the case for another study of these cables in flay configuration, where the screens are cross bonded. This corresponds to the single point bonding arrangement, where circulating currents are not present. Therefore, in ordered to verify whether the induced circulating currents are calculated correctly in GRØFT for this case study, the analytical model corresponding the cables in flat configuration, however, solid bonded, was prepared in accordance with IEC.

The TB 880 analytical model was supplied with the loss factor λ'_1, that accounts for the heat loss due to the induced circulating current in sheath. The cable rating is calculated similarly as in TB 880, except of the thermal resistance of surrounding medium T_4, that is modified according to IEC2 (ref. 4.2.3.3.4). Two separate resistances $T_{4\,n}$ and $T_{4\,d}$ are applied in the current rating equation of IEC1 (ref. 1.4.1.1):

The resistance applied in the nominator of the current rating equation:

$$T_{4\,n} = \frac{1}{2\pi}\rho\left\{ln\left(u_1 + \sqrt{u_1^2 - 1}\right) + ln\left[1 + \left(\frac{2L}{s_1}\right)^2\right]\right\} \tag{9.1}$$

The resistance applied in the denominator of the current rating equation:

$$T_{4\,d} = \frac{1}{2\pi}\rho\left\{ln\left(u_1 + \sqrt{u_1^2 - 1}\right) + \left[\frac{1+0.5(\lambda'_{11}+\lambda'_{11})}{1+\lambda'_{1m}}\right] ln\left[1 + \left(\frac{2L}{s_1}\right)^2\right]\right\} \tag{9.2}$$

A similar cable rating was obtained applying this approach for the case of these cables in flat configuration with cross-bonded sheath presented in TB 880.

As presented in Table 8.3, 400 kV cables solid bonded in flat configuration modelled in GRØF, results in ampacity very close to the one calculated with the IEC analytical model.

	Cable	400kV LPOF			
	Configuration	**Flat, solid bonded**			
Parameter		**Symbol**	**Unit**	**IEC 60287**	**GRØFT**
$I = 1001.2\ A$	Loss conductor[1]	Wc	W/m	12.62	12.60
	Loss Screen[1]	Ws	W/m	32.11	32.20
	Dielectric loss of insulation	Wd	W/m	5.950	5.950
	Max temperature of conductor	T_{max}	°C	85.00	84.3
Permissible current rating/ampacity		I	A	**1001.2**	**1006.5**
[1] Heat loss related to L1 (middle phase)					

TABEL 8.3 COMPARION OF RESULTS BETWEEN TB880 AND GRØFT FOR CASE 5

In order to explain the discrepancies for cables in trefoil, presented in Table 8.1, two simplified models of cable (see Figure 8.1) were analyzed for varying sheath thickness t_s. The calculations are performed in GRØFT and with the use of the analytical model built in accordance with IEC. The reference conditions consider the cables buried 1 m under the ground surface with the reference temperature of 20 °C. The thermal resistivity of surrounding masses is set to 1 m.K/W.

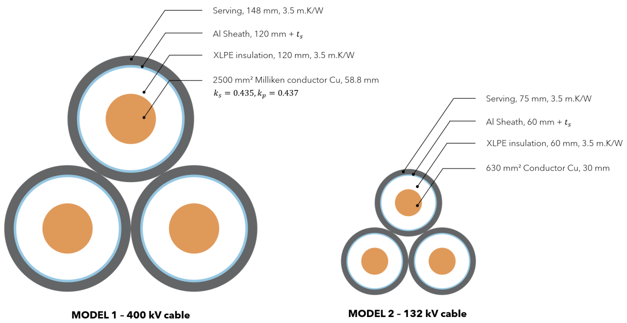

FIGURE 8.1 SIMPLIFIED MODELS OF CABLES IN TREFOIL USED TO COMPARE CALCULATIONS PERFORMED IN GRØFT AND IN ACCORDANCE WITH IEC

The comparison of the resulting temperatures of conductor and induced current in sheath, obtained with IEC calculations and GRØFT, are presented in Figure 8.2 and 8.3. For 400 kV cable (MODEL 1), the proximity of cable installation seems to have a considerable effect on the induced circulating current in sheath. For 132 kV cable (MODEL 2), with much less cross-sectional area of sheath, the difference of induced circulating current, between GRØFT and IEC results, is not noticeable.

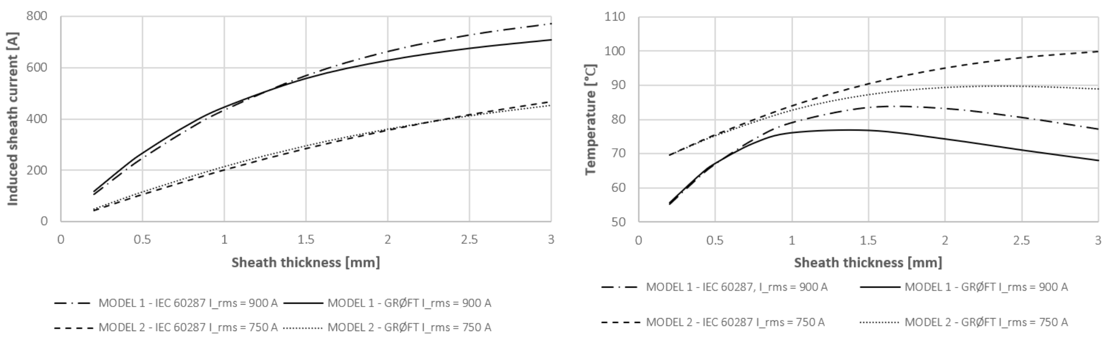

FIGURE 8.2 COMPARISON OF GRØFT AND IEC CALCULATIONS BASED ON MODEL 1 AND MODEL 2 FOR VARYING SHEATH THICKNESS

The difference of temperatures across sheath is analyzed in GRØFT for MODEL 1 and MODEL 2, as presented in Figure 8.3. Based on these results, it is clear that the thickness of the sheath will be the parameter determining of how close to the isotherm approximation the circumference of sheath will be. The effect of the circumferential heat conduction of metallic layer is not considered in the IEC calculations.

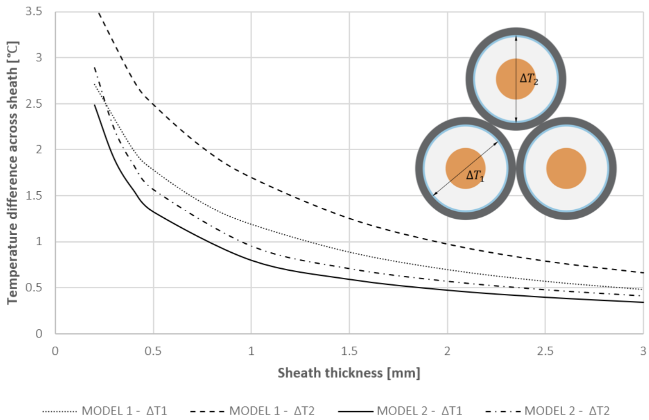

FIGURE 8.3 TEMPERATURE DROP ACROSS CABLE SHEATH FOR MODEL 1 AND MODEL 2 FOR VARYING SHEATH THICKNESS

According to IEC, the formula describing the loss factor λ'_1 assumes the uniform distribution of current in sheath for all formations of cable installation. The proximity of cables has, however, a considerable effect on the distribution of induced current in sheath, therefore this formula may not be suitable for cable design implementing sheath layer with a considerable cross-sectional area. According to IEC1 (ref. 5.3.7.1), for the aluminum sheathed cables, with diameter greater than 70 mm and thickness greater than usual, the terms describing the heat losses in sheath shall be evaluated. However, the standard does not indicate which terms and how the evaluation should be performed; neither how the term "greater than usual" is defined.

For cable installation in close proximity and solid bonded, the thickness of sheath defines the rate of distortion of heat around the cable. Furthermore, as the thickness of sheath increases, the reduction of the proximity effect is observed in the conductor, i.e. the distribution of current in sheath approaches the single cable arrangement as the thickness is greater.

Based on the presented study, the conclusion is made, that analysis performed in GRØFT is much more accurate than the IEC calculations. The phenomenon of proximity presented in this study should be taken into account in the IEC standard. The valuable input to the presented problematics was made by Chatzipetros and Pilgrim [6] who investigated the loss factor λ'_1 for large conductor cables.

9. CASE STUDY 9 – 110 KV RETROFITTED CABLE

The ampacity for the 110 kV retrofitted cable does not correspond to the ampacity reported in TB 880 (see Table 9.1). Comparable heat losses, however, indicate that it is due to the difference in the thermal model.

	Cable	2X(FL)2YVF ST2Y 3x400 RM 64/110 kV				
	Configuration	Single cable in pipe, solid bonded				
Parameter		Symbol	Unit	TB 880	GRØFT[1,3]	GRØFT[2,3]
$I = 572.4\ A$	Loss conductor	Wc	W/m	20.87	19.80	19.80
	Loss Screen	Ws	W/m	0.89	0.64	0.64
	Loss armor	Wa	W/m	2.86	1.68	1.68
	Dielectric loss of insulation	Wd	W/m	0.30	0.30	0.30
	Max temperature of conductor	T_{max}	°C	90.00	80.7	80.9
Permissible current rating/ampacity		I	A	572.4	609.8	609.5

[1] Cable in PE pipe
[2] Cable in steel pipe with PE covering

TABEL 9.1 COMPARION OF RESULTS BETWEEN TB880 AND GRØFT FOR CASE 9

According to the specification described in TB 880, the model of 100 kV retrofitted cable disregards the heat loss in steel pipe, in which the cables are installed. Only the thickness of PE covering is considered. The resistance of air in the pipe is calculated similarly as in case #0-2 and #0-3. Cable is placed in the center of pipe, however different parameters of U, V and Y, that correspond the steel pipe-type cables, are applied. In TB 880, the thermal resistance of gaps between the outer sheath of each cable and bedding is not given. In practice, the air would be present in those gaps, suppressing the heat dissipation from cables. The model presented in TB 880 introduced several geometrical approximations that aimed at approximating the unregular shape of cable.

Taking into consideration the abovementioned specification, the detailed comparison of the calculated ampacity for this cable, between TB 880 and GRØFT, is not possible. The thermal model, that is solved in GRØFT is much more precise than analytical expressions found in TB 880, especially for not concentrical and unsymmetrical cables. In GRØFT cables is placed on the bottom of the pipe, that contributes to the heat dissipation. Furthermore, the pipe in GRØFT may be modelled as the approximation of the steel pipe with PE-covering, however no heat losses in pipe will be calculated. The pipe must be modelled with a full thickness and modified thermal resistivity ρ_{eqv} as follows:

$$T"_{4\,steel\,pipe} = \frac{\rho_{steel}}{2\pi} ln \frac{D_i + 2 \cdot t_{steel}}{D_i}\ [m.K/W] \tag{9.1}$$

$$T"_{4\,PE} = \frac{\rho_{PE}}{2\pi} ln \frac{D_o}{D_i + 2 \cdot t_{steel}}\ [m.K/W] \tag{9.2}$$

$$T"_4 = T"_{4\,steel\,pipe} + T"_{4\,PE} \tag{9.3}$$

$$\rho_{eqv} = 2\pi \cdot T"_4 \cdot \left(ln \frac{D_o}{D_i}\right)^{-1} [m.K/W] \tag{9.4}$$

Where:

$T"_4$	-	Thermal resistance of pipe [m.K/W]
D_o	-	External diameter of pipe [mm]
D_i	-	Internal diameter of pipe [mm]
t_{steel}	-	Thickness of steel pipe [mm]
ρ	-	Thermal resistivity of material (*steel = 0.022 m.K/W* and *PE = 3.5 m.K/W*)

10. CASE STUDY 10 – PILC 8/10 KV 3 x 96 AL

The slight difference equal to 6.7 A in the resulting ampacity is reported for analyzed PILC 8/10 kV cable (Table 10.1).

	Cable			**PILC 8/10 kV 3x96Al**	
	Configuration			**Single cable, solid bonded**	
Parameter		**Symbol**	**Unit**	**TB 880**	**GRØFT**
$I = 165.74$	Loss conductor	Wc	W/m	29.61	30.0
	Loss Screen	Ws	W/m	0.047	0.057[1]
	Armor loss	Wst	W/m	0.012	0.008[1]
	Dielectric loss of insulation	Wd	W/m	0.038	0.038
	Max temperature of conductor	T_{max}	°C	55.0	53.5
Permissible current rating/ampacity		I	A	**165.74**	**159.0**
[1] Armor is modelled as sheath, therefore in GRØFT the heat losses in sheath are related to both lead sheath and steel tapes. The values in the table were fetched by hand from .mph file of cable model.					

TABEL 10.1 COMPARION OF RESULTS BETWEEN TB880 AND GRØFT FOR CASE 10

The cable design introduces galvanized steel tapes in which, as described in TB 880, the hysteresis losses shall be considered. GRØFT does not support calculations of these losses, however, as they account only for 0.1 % of total heat loss in cable, it seems reasonable to use GRØFT for cable rating in that case. The steel tapes are therefore modelled in GRØFT as sheath. The material properties for this layer must be thereafter adjusted, as in GRØFT there is no material representation for galvanized steel. In the presented study, stainless steel is used instead.

The presented approach to the analysis of cable may be considered as accurate, as long as the calculation of the rate of the heat losses in armor is performed by hand according to IEC in preceding analysis. The simplification made for steel armor layer led to minor changes of the cable current rating.

REFFERENCES

[1] CIGRE, TB 880: Power cable rating examples for calculation tool verification, WG B1.56, 2022.

[2] G. J. Anders, Rating of Electrical Power Cables:Ampacity Computations for Transmissio, Distribution, and Industrial Applications, McGraw-Hill Professional; 1st edition, November 1, 1997.

[3] IEC 60287-2-1 Electric cables - Calculation of the current rating - Part 2-1: Thermal resistance - Calculation of thermal resistance.

[4] E. Eberg and S. M. Hellesø, "Simplified Model for Heat Transport for Cables in Pipes," IEEE Transactions on Power Delivery, vol. 37, no. 5, pp. 3812-3822, 2021.

[5] T. E. U. G. D. R. a. L. .. K. G. T. Hollands, "Free Convective Heat Transfer Across Inclined Air Layers," Journal of Heat Transfer , vol. 98, pp. 189-193, 1976.

[6] Y. A. Cengel and A. J. Ghajar, Heat and Mass Transfer: Fundamentals & Application, Fifth Edition, McGraw-Hill Education, 2015.

[7] D. Chatzipetros and J. A. Pilgrim, "Impact of Proximity Effects on Sheath Losses in Trefoil Cable Arrangements," IEEE Transactions on Power Delivery, vol. 35, no. 2, pp. 455-463, 2020.

[8] G. D. Raithby and . K. T. Hollands, "A General Method of Obtaining Approximate Solutions to Laminar and Turbulent Free Convection Problems," Elsevier, 1975.

[9] COMSOL, Heat Transfer Module, User`s Guide, COMSOL 6.2, 2023.

[10] NEK IEC 60287-1-1:2006 Calculation of the current rating Part 1-1: Current rating equations (100% load factor) and calculation of losses, Norsk Elektroteknisk Komite.

APPENDIX 1

The equivalent conductivity of air layer k_{eqv} represents the heat transfer by means of convection, radiation and conduction. The model with implemented k_{eqv} is then solved in GRØFT only for conductive heat transfer. The derivation of k_{eqv} is presented in this appendix.

A.1. EQUIVALENT THERMAL CONDUCTIVITY OF AIR LAYER

The rate of heat transfer Q between concentric cylinder considers the convective, conductive and radiative heat transfer components. The rate of heat transfer by means of conduction and convection is substituted with the effective rate Q_{eff}:

$$Q = Q_{cond} + Q_{conq} + Q_{rad} \ [W/m] \tag{A.1}$$

$$Q = Q_{eff} + Q_{rad} \ [W/m] \tag{A.2}$$

The analytical solution for solving the heat transfer in the air gap between the cable and pipe, where the cable is place in a center of the pipe, implements the equivalent heat transfer coefficient of air h_{eqv} that consider all heat transfer components, i.e. conduction, convection and radiation. The heat transfer coefficient by means of conduction and convection is substituted with the effective heat transfer coefficient h_{eff}:

$$h_{eqv} = h_{cond} + h_{conv} + h_{rad} \ [W/m^2K] \tag{A.3}$$

$$h_{eqv} = h_{eff} + h_{rad} \ [W/m^2K] \tag{A.4}$$

The rate of the heat transfer coefficient between infinitely long concentric cylinders (cable and pipe):

$$Q = -kA\frac{dT}{dr} \ [W/m] \tag{A.5}$$

$$\int_{r_i}^{r_0} \frac{Q}{A} dr = -\int_{T_i}^{T_0} kdT$$

(A.6)

$$\int_{r_i}^{r_0} \frac{Q}{2\pi r} dr = -\int_{T_i}^{T_0} kdT$$

(A.7)

$$Q = 2\pi k_{eqv} \frac{T_i - T_0}{ln \, {}^{r_o}/_{r_i}}$$

(A.8)

$$Q = \frac{\Delta T}{R} = h_{eqv} A_i \Delta T = h_{eqv} \pi D_i \Delta T \ [W/m] \tag{A.9}$$

The conduction resistance of the cylindrical layer R is:

$$R = \frac{ln \, {}^{D_o}/_{D_i}}{2\pi k_{eqv}} [K/W] \tag{A.10}$$

The equivalent thermal conductivity k_{eqv} is then derived as:

$$h_{eqv} = \frac{1}{R\pi D_i} \; [W/m^2K] \quad (A.11)$$

$$h_{eqv} = \frac{2\pi k_{eqv}}{ln^{D_o}/_{D_i}\pi D_i} \; [W/m^2K] \quad (A.12)$$

$$k_{eqv} = \frac{D_i h_{eqv} ln^{D_o}/_{D_i}}{2} [W/mK] \quad (A.13)$$

A2. RADIATIVE HEAT TRANSFER COEFFICIENT

$$h_{rad} = \frac{\sigma F_{1-2}\varepsilon({T_i}^4 - {T_o}^4)}{\Delta T(2-\varepsilon)} [W/m^2K] \quad (A.14)$$

The rate of heat transfer Q_{rad} between infinitely long concentric cylinders, by means of radiation, may be described with the following equation:

$$Q_{rad} = h_{rad} A_i \Delta T = h_{rad}\pi D_i \Delta T \; [W/m] \quad (A.15)$$

A.3. EFFECTIVE HEAT TRANSFER COEFFICIENT (CONDUCTION AND CONVECTION) [7]

$$h_{eff} = \frac{2\pi k_{eff}}{ln^{D_o}/_{D_i}\pi D_i} [W/m^2K] \quad (A.16)$$

$$\frac{k_{eff}}{k} = N_u = 0.386\left[\frac{Pr}{0.861+Pr}\right]^{0.25} {Ra^*}_{cc}{}^{0.25} \quad (A.17)$$

$$k_{eff} = k \cdot 0.386\left[\frac{Pr}{0.861+Pr}\right]^{0.25} {Ra^*}_{cc}{}^{0.25} \; [mK/W] \quad (A.18)$$

$$Ra^*_{cc} = \frac{\left(ln\frac{D_o}{D_i}\right)^4}{b^3\left(\frac{1}{D_i}^{0.6} + \frac{1}{D_0}^{0.6}\right)^5} Ra_b \quad (A.19)$$

$$Ra_b = \frac{g\beta(T_i - T_0)b^3}{v^2} Pr = \frac{g\beta\rho(T_i - T_0)b^3}{\mu\kappa} \quad (A.20)$$

$$Pr = \frac{C_p\mu}{k} \quad (1.21) \qquad \kappa = \frac{k}{\rho C_p} \quad (1.22) \qquad v = \frac{\mu}{\rho} \quad (A.23)$$

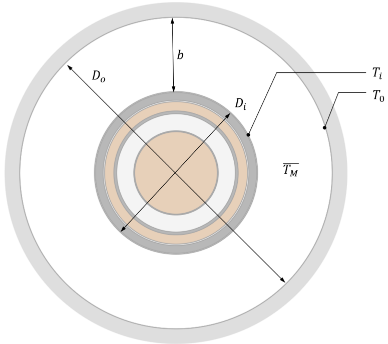

FIGURE A-2 PARAMETERS OF COAXIAL CYLINDERS (CABLE AND PIPE)

Symbol		**Parameter**	**Unit**
Nu_L	-	Nusselt number	-
Pr	-	Prandtl number	-
C_p	-	specific heat capacity	$J/((kg\cdot K))$
μ	-	dynamic viscosity of fluid	$Pa\cdot s = N\cdot s/m^2$
k	-	thermal conductivity of air	$W/(m\cdot K)$
$Ra^*{}_{cc}$	-	Modified Rayleigh number for concentric cylinders	-
D_i	-	Diameter of internal cylinder	m
D_0	-	Diameter of external cylinder	m
b	-	Characteristic length	m
Ra_b	-	Rayleigh number for characteristic length	-
κ	-	thermal diffusivity of air	m^2/s
v	-	kinematic viscosity of fluid	m^2/s
g	-	Gravitational acceleration	m/s^2
β	-	Volumetric coefficient of fluid expansion	$1/K$
ρ	-	Air density	kg/m^3
T_i	-	Temperature of internal cylinder	K
T_0	-	Temperature of external cylinder	K
$\bar{T}_M$	-	Average temperature of air	K

The effective rate of heat transfer Q_{eff} between infinitely long concentric cylinders, by means of convection and conduction, may be described with the following equation:

$$Q_{eff} = \frac{2\pi k_{eff}(T_i - T_0)}{ln\frac{D_o}{D_i}}[W/m] \quad (A.24)$$

APPENDIX 2

The effective conductivity of air layer k_{eff} for natural convection in horizontal enclosure proposed by Hollands et al., **Error! Reference source not found.**, in a function of the temperature of air, θ_{air} in range of 240 – 450 K, is described as follow:

$$k_{eff}(\theta_{air}) = Nu \cdot k_{air}\ [W/mK] \tag{A.25}$$

Where:

Nu - Nusselt number

$$Nu(\theta_{air}) = 1 + 1.44 \cdot max\left(1 - \frac{1708}{Ra}, 0\right) + max\left(\frac{Ra^{1/3}}{18} - 1), 0\right)$$

Ra - Raileigh number

$$Ra = \frac{g\beta(\theta_1 - \theta_2)s^3}{v^2} Pr$$

k_{air} - Thermal conductivity of air

$$k_{air}(\theta_{air}) = 10^{-8} \cdot (-27997.7 + 989.998\theta_{air} - 3.54283\theta_{air}^2)[W/(K.m).]$$

g - Gravitational acceleration $[m/s^2]$

s - Distance between hot and cold surface (internal height of trough) $[m]$

v - Kinematic viscosity of air $[m^2/s]$

$$v(\theta_{air}) = 10^{-11} \cdot (-376936 + 3780.05\theta_{air} + 9.114229\theta_{air}^2)[m^2/s]$$

β - Coefficient of volumetric expansion [8]

$$\beta = -\frac{1}{\rho_{air}(\theta_{air})} \cdot \frac{d\rho_{air}(\theta_{air})}{d\theta_{air}} [1/K]$$

ρ_{air} - Density of air

$$\rho_{air} = \frac{352.64}{\theta_{air}} [kg/m^3]$$

Pr - Prandtl number

$$Pr(\theta_{air}) = 0.833209 - 0.5823345\theta_{air} \cdot 10^{-3} + 0.5523336\theta_{air}^2 \cdot 10^{-6}$$

θ_1 - (Hot) Temperature of bottom surface $[K]$

θ_2 - (Cold) Temperature of top surface $[K]$

The rate of heat transfer Q_{nc} by the natural convection from the horizontal plate facing upwards or downwards, is expressed as follows

$$Q_{nc} = q_s A_s = h_{conv} A_s(\theta_1 - \theta_2)\ \ [W]$$

$$Q_{nc} = \frac{Nu \cdot k_{air}}{L} A_s(\theta_1 - \theta_2)\ [W]$$

Where:

Nu - Nusselt number for horizontal plate facing upwards

$$Nu(\theta_{air}) = 0.54{R_{a_L}}^{1/4}$$

Nusselt number for horizontal plate facing downwards

$$Nu(\theta_{air}) = 0.27{R_{a_L}}^{1/4}$$

L - Characteristic dimension (for surface A_s) $[m]$

$$L = \frac{A_s}{perimeter\ of\ A_s}$$