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Assessment of the thermal effect of biofouling on the submarine dynamic cable of floating offshore wind turbines

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ABSTRACT: Floating offshore wind turbine (FOWT) plays a significant role in meeting emission targets over the next 20 years. The dynamic submarine electrical cable (DSEC) is a key component of FOWT. Its electric insulation system is intended to withstand a maximum conductor temperature of 90°C. However, biofouling growth, particularly mussel growth, can modify heat transfer around the cable and thus the maximum conductor temperature, as well as temperature fluctuation, affecting fatigue lifetime. In our work, we thermally characterize mussels of various ages. The results revealed that the effective thermal conductivity of juvenile mussels is lower than that of mixed and only adult mussels. This variation in effective thermal conductivity with mussel's age is related to the water porosity of the mussel's layer. Using a numerical simulation, it founds that the thermal effect of the resulting global thermal resistance can lead the DSEC conductor wire to either overheat or cool down depending on the mussel's age.

1 INTRODUCTION

Sustainable or renewable energy is regarded as a primary solution to global warming; it significantly improves the environment by lowering CO² emissions. The offshore wind turbine is one of the most sophisticated renewable energy technologies (OWT). OWTs are classified into two types: floating offshore wind turbines (FOWTs) and bottom-fixed offshore wind turbines (BFOWTs). Water depth increases with distance to the coast, and FOWT are expected to meet these requirements for medium (> 60 m) (Benifla et al. 2022) or deep (> 150 m) water depth. Any offshore wind farm faces significant challenges in transporting produced energy to shore. A dynamic cable is needed to connect the floating hull to the main export cable on the seafloor in floating systems. According to the oil industry's experience with floating offshore installations, the greatest stresses are manifested at the head of the cable, that is, at the point of connection with the part fixed to the float. A bending device with floats and a tensioner is used to shape the section just before the connection into a "s" shape to reduce these stresses and thus fatigue of this section of the cable (Cruciani, 2019). One of the main challenges of the FOWT is the technical design of power cables and electrical connectors. Submarine power cable is classified into two types: static cable, which sits on top of or is buried beneath the seafloor, and dynamic cable (or umbilical), which is deployed through the water

column between the surface and the seafloor. This dynamic cable is affected by the movement of the floating platform, as well as wave excitation and currents. As a result, while dynamic power cables are an important component of electrical connections, their design remains a challenge for manufacturers, as it must account for electrical, mechanical, and thermal concerns. Any external factor that reduces its efficiency will result in reduced energy reception. Biofouling is a complex, dynamic, and a lengthy procedure involving a variety of biological mechanisms that are not fully comprehended (Weerheim et al. 2018). Mollusc bivalves, particularly mussels, are a common and problematic fouling element assembly in ship's sea chests and pipework (Sievers et al. 2019 & Valdez et al. 2016). These species are known to be dominant along the Atlantic coast (Schoefs et al. 2022, Marty et al. 2021). Indeed, biofouling growth, particularly mussel growth (Fig. 1), can alter heat transfer around the cable, affecting cable temperature, whereas the cross-linked polyethylene (XLPE) electric insulation system of dynamic submarine electrical cable (DSEC) is designed to support a maximum copper wire temperature of only 90°C continuously, according to IEC standard (IEC 2014). This maximum conductor temperature is considered a limit to avoid wire insulation (XLPE) degradation in long-term conditions. Therefore, it's critical to investigate the thermal effect of mussels around the cable to see if it affects heat transfer between the cable and the water in a positive or negative way. To accomplish this, the mussels

should be thermally characterized, followed by an examination of the effect of mussel biofouling on the temperature of the DSEC copper conductor wire. To our knowledge, there have been no previous studies on the thermal characterization of mussels around cables. This study measures the heat transfer coefficient of the water surrounding the mussels as well as the "effective" thermal conductivity of different mussel age classes (juvenile (six-month-old), mixed (juveniles and adults), and adults (12-month-old) (Fritdge et al. 2013). Furthermore, numerical simulations of the temperature field of DSEC colonized with mussels of varying ages are carried out. The experimental measurement of the effective thermal conductivity of various ages of mussels and the heat transfer coefficient of the water around them for uniform and non-uniform colonization will be presented in the following section.



Figure 1. Juvenile Mussel's patch (6 months) – Aiguillon sur mer, France, July 8th 2020.

2 MUSSELS' THERMAL CHARACTERIZATION

2.1 Thermal Characterization of Mussels for Uniform Colonization Around the Tube

Different ages of mussels were thermally characterized in this section by fixing them with a uniform colonization shape around the experimental tube, which means that mussels of the same thickness cover the entire experimental tube.

2.1.1 Measurement method

An experimental aluminum tube colonized with mussels of uniform shape, as shown in Figure 2, is immersed in a tank of sea water, and a power provided by the heating elements inside the tube is used to achieve a steady state temperature with a temperature difference of about 4 K to 10 K between both sides of the mussel layer. The effective thermal conductivity of the mussels is calculated using a 1D analytical stationary model based on Fourier's law (Maksassi et al. 2022). To validate the measurement method, the thermal conductivity of a double-sided foam adhesive is compared to that of a hot guarded plate device. The result shows that the thermal conductivity computed

using equation (1) and measured with our experimental setup with aluminum tube was $0.052 \text{ W.m}^{-1}.\text{K}^{-1}$ for double sided tape adhesive whereas the one with the HGP device was equal to $0.055 \text{ W.m}^{-1}.\text{K}^{-1}$, therefore with only a 5.45% and 3.64% relative discrepancy, respectively. This confirms that the tube extremities connected to the sample holder are well insulated thermally. In other words, the axial heat flux along the aluminum tube is negligible in comparison to the radial one, which explains why the direction along the tube length is ignored in our thermal models (analytical and numerical). The heat transfer coefficient of the water surrounding the mussels (h_w) is also calculated using Newton's law. It is validated by comparing the result of the heat transfer coefficient of water around a tube without mussels to two literature correlations (Churchill & Chu and Morgan (Incorpera et al. 2007)). The discrepancy between the experimental value h_w and the one provided by Morgan correlation is equal to 6%, which is less than the discrepancy value of 29% provided by Churchill & Chu's correlation. This is due to the fact that Churchill & Chu's correlation was set for a wide range of Rayleigh number ($Ra_D \leq 10^{12}$), whereas Morgan's correlation is related to a narrow range of Rayleigh number (Table 9.1 in (Incorpera et al. 2007)). Furthermore, the heat transfer coefficients derived from the correlations were applied to an isothermal horizontal cylinder, whereas the experimental tube in our case is not completely isothermal. As a result, the difference in experimental and theoretical correlation values is acceptable.

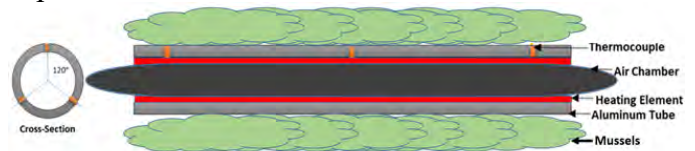


Figure 2. Schematic for the experimental tube.

2.1.2 Effective Thermal Conductivity of Mussels and Heat Transfer Coefficient of the Water Around Measurement Results

The effective thermal conductivity of mussels of various ages in the case of uniform colonization, which means uniform thickness along the colonized material, is shown in Table 1, with juvenile, mixed, and adult mussels having thicknesses of 4 cm, 6 cm, and 7 cm, respectively. The effective thermal conductivity of juvenile, mix (juvenile and adult), and adult mussels is 4.4 , 8 , and $12.8 \text{ W.m}^{-1}.\text{K}^{-1}$, respectively. As the relative uncertainty on k_{biof} measurement is less than 9%, the differences between the various types of colonization is significant. One possible explanation for these disparities is that mussel volume increases with age. The water porosities of the three biofouling materials then increase with mussel age due to differences in mussel size. As a result, more

natural convection can be expected inside older bio-fouling (in mussel pore space), resulting in higher effective thermal conductivity. Furthermore, Table 1 shows that the heat transfer coefficients of the water surrounding the juvenile, mix (juvenile and adult), and adult mussels are 3395, 873, and 2682 $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$, respectively. However, because the position of the external thermocouple is not precise (less than 5 mm) and the temperature difference between the mussel's external layer and the water is small (less than 0.4 °C), the relative uncertainty ranges from 19 to 37 percent. However, given the relatively high value of convective heat transfer of water around mussels, its contribution to overall thermal resistance between the cable and the external water is minor in comparison to mussels' effective conductive resistance (Maksassi et al. 2022).

Table 1. Effective thermal conductivities of mussels of various ages and the heat transfer coefficient around them.

Mussels type	k_{biof}	Relative	h_w	Relative
	$\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$	Uncertainty	$\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$	Uncertainty
		%		%
Juvenile	4.4	9	3395	33
Mix (juvenile and adult)	8.0	6.5	873	19
Adult	12.8	7.6	2682	37

2.2 Thermal Characterization of a Non-Uniform Colonization of Biofouling around the Tube

In practice, light comes from above, mussel growth occurs primarily on the tops of horizontal electric cables undersea. Due to the more complicated geometry in this case, the effective thermal conductivity of mussels of various ages and the heat transfer coefficient of the water surrounding the mussels are estimated using a numerical method (finite elements via COMSOL) to solve the 2D heat transfer equation and a robust minimization technique (simplex method) to estimate the effective thermal conductivity of mussels from inverse analysis in order to minimize the sum of the estimates. The external temperature of the system is the one of the water and the heat rate of power in the 2D thermal model. As shown in Figure 3, the estimation is made for various colonization distribution configurations (25 percent, 50 percent, and 100 percent colonization) around the heated covered polyethylene aluminum tube.

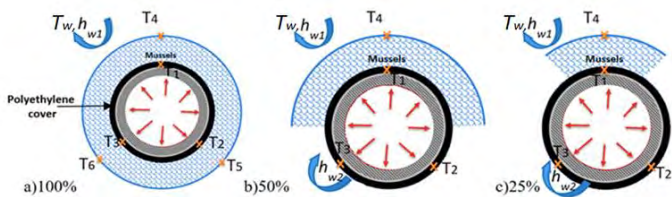


Figure. 3 Various colonization distribution configurations around the heated covered polyethylene aluminum tube. (a) 100% colonization, (b) 50 % colonization and (c) 25% colonization. (Maksassi et al. 2022)

3 THERMAL EFFECT OF MUSSELS ON THE DSEC COPPER WIRE

In Section 2, we showed that the age of the mussels alters the water porosity of the biocolonization, affecting global thermal resistance. It was demonstrated that the thermal resistance of a mussel layer can be lower or higher than convective resistance without mussels. Analyzing the effect of colonization on temperature distribution in a real submarine power cable could be interesting. As described in Section 2.1.2, the effective conductive resistance of juvenile mussels is greater than the convective resistance around the tube in the absence of mussels; however, the effective conductive resistance of mixed mussels is slightly greater and the effective conductive resistance of adult mussels is slightly lower. As a result, mussel deposits on the surface of a marine power cable can form an insulating layer, increasing thermal resistance. An analytical model based on an international standard is used in this section to calculate the permissible current rating for a given operating temperature. This produces a power that can be imposed in a 2D numerical simulation model (finite elements via COMSOL) to investigate the thermal effect of mussels of varying ages on the temperature of the DSEC copper wire.

3.1 Analytical Model Based on IEC Standard

Under steady-state conditions, the permissible current rating in accordance with operating temperature is calculated using IEC standards 60287-1-1 (IEC 2014) and 60287-2-1 (IEC 2015). It denotes a constant current load (100 percent load factor) that is only enough to generate the maximum conductor temperature asymptotically and assumes that the surrounding ambient conditions are constant. This method is widely used throughout the world. It covers medium to high voltage cables, a variety of installation methods, and a current rating and loss formula. The main goal is to determine the relationship between the cable and the factors influencing heat dissipation, such as cable component thermal resistance, load, and surrounding environment. To demonstrate the method, we use a data-available cable: a 20 kV cable used in the OMDYN2 project. It is a cross-linked polyethylene insulated dynamic submarine electrical cable (DSEC) capable of continuously maintaining a maximum conductor temperature of 90 °C. It is made up of $3 \times 50 \text{ mm}^2$ copper conductors that are covered with a double wire armor to increase torsional stiffness due to

dynamical application and to protect it from mechanical stress, floating debris, and friction caused by the cable touching the seabed. Figure 4, shows the high-voltage dynamic cable's complex hierarchical cross-sectional structure.

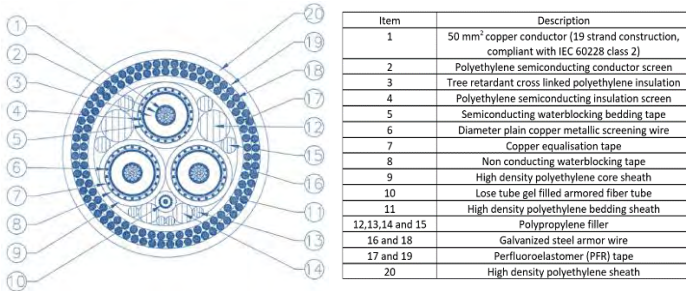


Figure 4. Cross section of a three phases DSEC. (Maksassi et al. 2022)

Figure 5, shows a physical representation of the cable and its surroundings as a network of combined thermal resistances. All thermal resistances are calculated in accordance with IEC standard 60827-2 (IEC 2015), where R_1 represents the thermal resistance per unit length between one conductor and the sheath ($K.m.W^{-1}$), R_2 represents the thermal resistance per unit length of the fillers and bedding under the armor ($K.m.W^{-1}$), R_3 represents the thermal resistance per unit length of the cable's external serving ($K.m.W^{-1}$), and R_4 represents the thermal resistance per unit length between the cable surface and the surrounding medium ($K.m.W^{-1}$), T_c (K) is the operating temperature of DSEC conductor, T_a (K) represents the ambient temperature, T_s (K) represents the sheath temperature, and T_0 (K) represents the outer serving temperature.

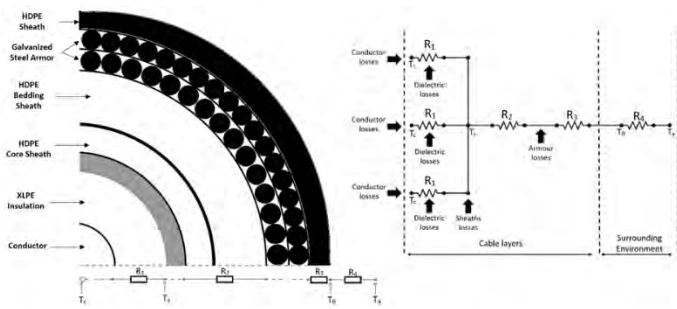


Figure 5. Network of thermal resistances representing steady state heat transfer in a three core submarine cable and its surrounding environment. (Maksassi et al. 2022)

Using Ohm's law and the steady-state condition, which means that when the current flow through the cable is constant and the temperature of the cable is constant. As a result, the maximum current that an AC cable can deliver is obtained as shown in the following equation:

$$I = \left[\frac{\Delta\theta - W_d [0.5 R_1 + n (R_2 + R_3 + R_4)]}{R_{AC} R_1 + n R_{AC} (1 + \lambda_1) R_2 + n R_{AC} (1 + \lambda_1 + \lambda_2) (R_3 + R_4)} \right]^{0.5} \quad (1)$$

where I represents the current flowing in a single conductor (A), $\Delta\theta(K) = T_c - T_a$, n represents the number of copper conductors in the cable. λ_1 and λ_2 are calculated using IEC standard 60287-1 (IEC 2014), where λ_1 is the ratio of losses in the metal sheath to total losses in all conductors in that cable, λ_2 is the ratio of losses in the armoring to total losses in all conductors in that cable. Also, R_{AC} and W_d are calculated using IEC standard 60287-2 (IEC 2015), where R_{AC} denotes the alternating current resistance per unit length of the conductor at maximum operating temperature ($\Omega.m^{-1}$) and W_d denotes the dielectric loss per unit length for the insulation surrounding the conductor ($W.m^{-1}$). The thermal resistances and the heat losses in the submarine power cable used for our calculations are shown in Table 2.

Table 2. Thermal resistances and heat losses in the submarine power cable.

Symbol	Material	Value
R_1	Thermal resistance between one conductor and the sheath per unit length ($K.m.W^{-1}$)	0.587
R_2	Thermal resistance of the bedding between the sheath and the armor per unit length ($K.m.W^{-1}$)	0.095
R_3	Thermal resistance of the cable's external serving per unit length ($K.m.W^{-1}$)	0.035
R_4	Thermal resistance between the cable surface and the surrounding medium per unit length ($K.m.W^{-1}$)	0.011
λ_1	Ratio of losses in the metal sheath to total losses in all conductors in that cable	0.05
λ_2	Ratio of losses in the armoring to total losses in all conductors in that cable.	0.112
R_{AC}	Alternating current resistance per unit conductor length at maximum operating temperature ($\Omega.km^{-1}$)	0.5
W_d	The dielectric loss per unit length of the insulation that surrounds the conductor ($W.m^{-1}$)	0.074

* These resistances are calculated for 90 °C operating temperature and 20 °C ambient temperature. (Maksassi et al. 2022)

3.2 Numerical Simulation of Temperature Field in a 2D DSEC

The thermal effect of mussels of various ages on the DSEC copper wire is investigated in this section by predicting the temperature distribution within the cable using a two-dimensional steady-state thermal model computed using finite elements (COMSOL software) with heat conduction equation using a mesh with 2000 to 5000 nodes in the biofouling region and in the DSEC.

As mentioned earlier, the DSEC is designed to support a maximum copper wire temperature of 90 °C. Therefore, for a maximum operating temperature of 90 °C and an ambient temperature of 20 °C, the permissible current rating (364 A) is calculated using equation (1). The obtained current rating (364 A) is then imposed in the numerical method of DSEC 2D thermal modeling (COMSOL software). Moreover, with an external temperature of 20 °C, a convective heat transfer coefficient ($247 W.m^2.K^{-1}$) is applied to the outer layer of the DSEC; this convective heat transfer coefficient is calculated using the classic natural convection formula (Morgan's correlation). The

steady-state temperature distribution in the cable is depicted in Figure 6. The maximum conductor temperature calculated using a two-dimensional numerical thermal model is 90.15 °C, which is near the maximum operating temperature of 90 °C. The numerical approach is validated because the simulation code (COMSOL) produces the same temperature as the IEC-60827 standard. After that, the numerical thermal model can be used to investigate the thermal effect of biofouling colonization on DSEC conductor temperature.

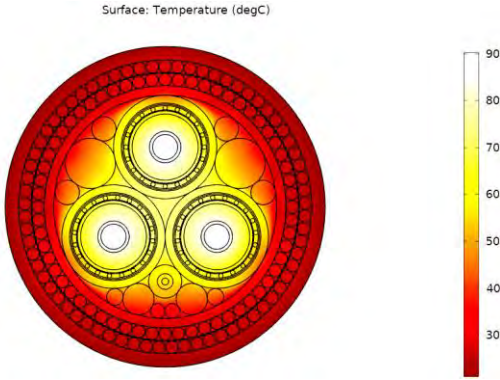


Figure 6. Simulation of the DSEC steady-state temperature distribution (°C) under rated load conditions. (Maksassi et al. 2022)

The thermal effect of mussels on DSEC conductor temperature is investigated by simulating it with an extra layer around the cable in COMSOL (Fig. 7). The effective thermal conductivity of the external layer and the heat transfer coefficient of the water around the mussels of various ages used in these calculations are those measured in Section 2.1.2 and shown in Table 1. It should be noted that the thicknesses of mussel layers of varying ages are implemented in the numerical simulation by defining the geometry of the mussel layer with the same thicknesses of mussel layers during thermal characterization (40 mm for juvenile, 60 mm for mix and 70 mm for adult mussels).

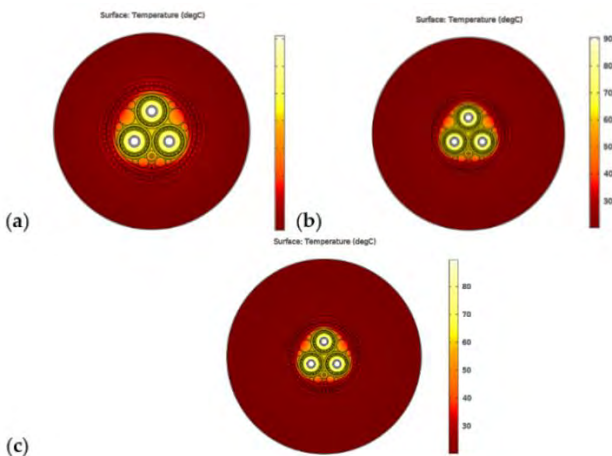


Figure 7. Steady-state temperature (°C) distribution for different ages of mussels (a) Juvenile, (b) Mix (c) Adult. (Maksassi et al. 2022)

Figure 8 shows that the DSEC conductor temperature T_c decreases with mussel age: 91.3 °C (juvenile), 90.6 °C (mix), and 89.6 °C (adult) (adult). As previously stated in Section 2.1.2, juvenile mussels have the greatest thermal resistance, and thermal resistance decreases with age due to an increase in water porosity. As a result, colonization of juvenile and mixed mussels on DSEC results in conductor temperatures higher than the maximum operating temperature (90 °C), but not for adult mussels.

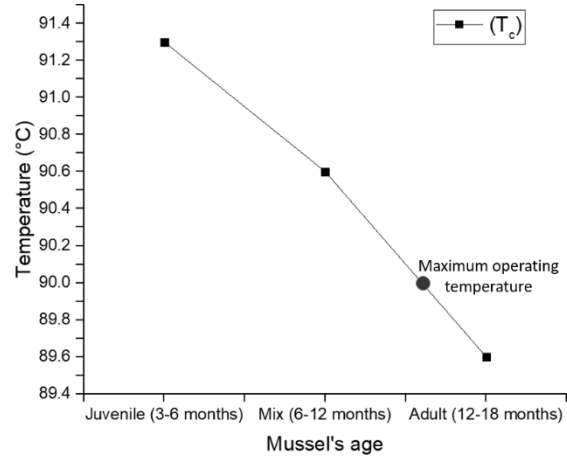


Figure 8. DSEC conductor temperature in function of mussel age. (Maksassi et al. 2022)

This result appears to imply that the conductor's temperature decreases with mussel age and can be as low as the temperature without mussels, which is used as a reference here. This opinion must be moderated due to several aspects of our research: (i) the experiments and simulations are carried out with a single layer of mussels of roughly equal thickness. In reality, a new layer of mussels grows on top of the existing one as time passes from one season to the next. Over time, the water porosity and effective thermal conductivity will evolve. This may overheat the conductor. (ii) As previously stated, effective thermal conductivity is proportional to natural convection in a porous medium composed of mussels. The temperature difference across the mussel layer causes this natural convection effect. The purpose of this study is to look into the impact of mussel colonization on the copper conductor temperature of an electrical cable with a maximum operating temperature of 90 °C. In this case, we used IEC-compliant power calculations in our numerical simulations. Then, we imposed the measured effective thermal conductivity of the various mussel layers. The power values used in the experimental measurement differ from the power calculated using the IEC standard, which is used in the numerical simulations. This results in a difference in ΔT between experimental measurements and numerical simulations, as shown in Table 3. This disparity in ΔT values is expected because the power imposed in numerical simulation differs from the power imposed in experimental measurement, and effective thermal conductivity depends on ΔT . This distinction has an

impact on the calculation of the simulated temperature of the copper conductor. As a result, the appropriate effective thermal conductivity of the mussels must be imposed in the numerical simulation to improve the accuracy of this temperature determination. We don't have access to the variation of this thermal property with ΔT at this point in our work. This problem will be addressed in our subsequent work.

Table 9. The temperature difference between the mussel layer's inner and outer radiuses.

Mussels Type	ΔT	ΔT
	(Measurement)	(COMSOL)
	K	K
Juvenile	10	3.3
Mix (juvenile & adult)	4.2	2.4
Adult	4.8	1.7

4 CONCLUSION

In this study, the thermal characterization of a mussel layer around a tube was carried out. The thermal properties of this natural medium (bio-fouling) are rarely measured in the marine energy literature. The experiments were extremely difficult because we had to complete all of them in 24 hours in order to keep the mussels alive. The thermal conductivity of different ages of mussels (juvenile, mix-juvenile and adult, and adult) as well as the heat transfer coefficient of the water around the mussels were measured in the uniform mussel colonization case. Due to the water porosity effect, juvenile mussels have the lowest effective thermal conductivity when compared to a mix of juvenile and adult mussels and adult mussels. The effect of water porosity has been highlighted and illustrated using a glass beads medium, where natural convection in the porous media significantly increases the thermal conductivity of the glass porous media. In addition, the thermal risk on the DSEC is assessed by estimating the temperature distribution within the electric cable covered with mussels of various ages and the type of colonization using a numerical code (COMSOL). Depending on the mussels' age and global thermal resistance, bio-colonization causes the cable to overheat with juvenile and mix (juvenile and adult) mussels and to cool down with adult mussels. These measurements were made for a specific thickness of mussel layer and do not account for the evolution of bio-colonization over time (multi-layer effects). This will be addressed in our subsequent work. The BIODYTHERM project plans a new measurement and thermal characterization campaign for different ages of mussels colonized naturally on four tubes submerged in the Atlantic Ocean and the Mediterranean Sea, with thermal conductivities measured as a function of the temperature gradient (ΔT) through the mussel layer. We expect some variation in the value of measured effective thermal conductivity with the ΔT because measurements were performed in a range of ΔT over the mussel's layer

between 4 K and 10 K in the current work. This effect will be studied in future measurements. This will allow us to run simulations with configurations that are more similar to actual experimental conditions.

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