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A THERMAL STUDY OF POWER CABLES COOLING IN TUNNELS

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Abstract. Power transmission through power cables installed in ventilated tunnels has been increasingly used worldwide and offers a complex thermal environment. Established correlations currently in use have been deduced from a non-fully developed turbulent flow. This paper details the experimental investigation of the heat transfer from a single cable in a fully developed turbulent air flow, with emphasis on the effect of the cable spacing from the tunnel wall. Nusselt numbers have been compared for different spacing and velocities. The overall heat transfer is found to be meaningfully lower than in previous studies and no threshold spacing value for the average heat transfer to decrease is clearly found. Thermal radiation is found to greatly impact the cable cooling profile.

Keywords : Power delivery, Forced convection, Radiation, Fully turbulent flow.

Nomenclature

D_e	Cable diameter	m	T_2	Thermal resistance of the heatshrink	m^2K/W
D_h	Hydraulic diameter	m	P_{tot}	Heating power	W/m
U	Mean axial velocity	m/s	P_{conv}	Convective power	W/m
ν	Kinematic viscosity	m^2/s	P_{ray}	Radiative power	W/m
μ	Dynamic viscosity	$kg/m.s$	L_e	Turbulent entrance length	m
C_p	Specific heat	$J/kg.K$	L_x	Cable spacing	m
λ	Thermal conductivity	$W/m.K$	a	Mock-up width	m
θ_s	Temperature at azimuthal location on the cable	$^{\circ}C$	Re_{D_e}	Reynolds number	$U \cdot D_e / \nu$
θ_{wall}	Wall temperature	$^{\circ}C$	Pr	Prandtl number	$C_p \cdot \mu / \lambda$
$\theta_{ambient}$	Ambient temperature	$^{\circ}C$	Nu_{D_e}	Local Nusselt Number	
$\bar{\theta}$	Mean azimuthal temperature	$^{\circ}C$	$\overline{Nu_{D_e}}$	Mean azimuthal Nusselt number	
			a/D_e	Aspect Ratio	

1. Introduction

Underground power transmission network are increasingly used across the world. Power cables laid in tunnels are transiting currents and then, heating the enclosed environment. The precise knowledge of the thermal environment in the tunnels is a key factor in the determination of the permissible current allowed to flow in the link (the cable rating).

Before 1972, this kind of air flow has been treated approximately with classical correlations established for forced convection in pipes as in Dittus–Boelter equation (1).

$$\overline{Nu_{D_h}} = 0.023 Re_{D_h}^{0.8} Pr^{0.4} \quad \text{for} \quad Pr > 0.5 \quad \text{and} \quad Re_{D_h} > 10\,000 \quad (1)$$

The reference laws for the heat transfer over heated cylinders has been proposed by Weedy and El Zayyat, 1972 [1]. The authors have done extensive testing with dummy cables placed in a wind tunnel of dimensions 2.13x1.67x4.5m, with several cable diameters and velocities from 0 m/s to 6 m/s. Single cable and typical group configurations used in practice have been studied in natural convection as well as forced convection and laws have been obtain in the form of equation (2).

$$\overline{Nu_{D_e}} = C Re_{D_e}^{0.65} \quad \text{for} \quad 6.25 \cdot 10^3 \leq Re_{D_e} \leq 5.0 \cdot 10^4 \quad (2)$$

with Reynolds number based on the cables diameters ranging between $6.25 \cdot 10^3$ and $5.0 \cdot 10^4$. The coefficient C is given for single cable and groups of three cables (vertical flat and trefoil formations).

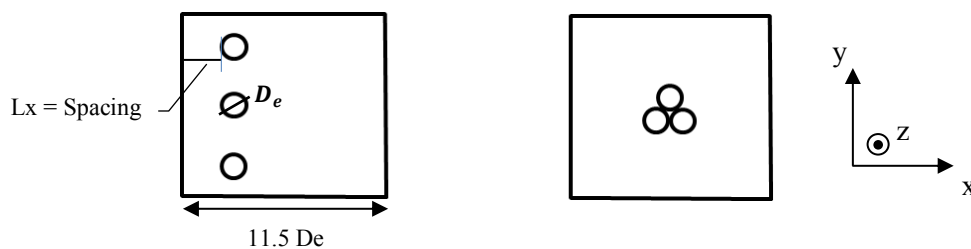


Figure 1 : Classical cable formation – vertical flat (left); trefoil (right)

More recent work done by Pilgrim [2] has pointed out the highly insufficient length of the test bench used in [1] to obtain a fully developed turbulent flow, leading to higher heat transfer estimate. Moreover, the presence of cleats to secure the cables to the wall in the middle of the test area act as heat sinks and break the development of the dynamic and thermal boundary layers. These factors would participate in the overestimation of the convective heat transfer coefficient and therefore the Nusselt correlation associated.

From a theoretical point of view, flows over long cylinders have been scarcely studied. [3][4] have studied the heat transfer from a heated cylinder of small size and concentric configurations with high aspect ratio ($D_{enclosure}/D_{cylinder}$). More information is available on the natural convection of enclosed cylinder, [5][6] have studied natural convection in an enclosed cylinder of small aspect ratio.

In order to have a better understanding of the heat transfer phenomena occurring with power cables installed in ventilated tunnels, an expurgated experimental study has been proposed. The key concerns have been allowing an appropriate entrance length for the turbulent flow and as little perturbation to the air flow as possible. The Nusselt laws derived from these test would serve as a basis for more complex setup.

The paper present the experimental setup used in this scope, and the experimental protocol is detailed. The results are then discussed in term of overall heat transfer before emphasising on the local behaviour in near wall configurations.

2. Experimental setup

2.1. Experimental apparatus

A tunnel mock-up has been designed in similitude with an actual power tunnel. Reynolds number based on the cable diameter range between $1.25 \cdot 10^4$ and $5.5 \cdot 10^4$. The original tunnel square section is represented by a 0.333 m square section and the mock-up length is 6.5 m long. The aspect ratio for a single cable configuration is $D_e/a = 11.5$. The dimensions are set for the maximum entrance length to be of 6 m for the maximum Reynolds number tested.

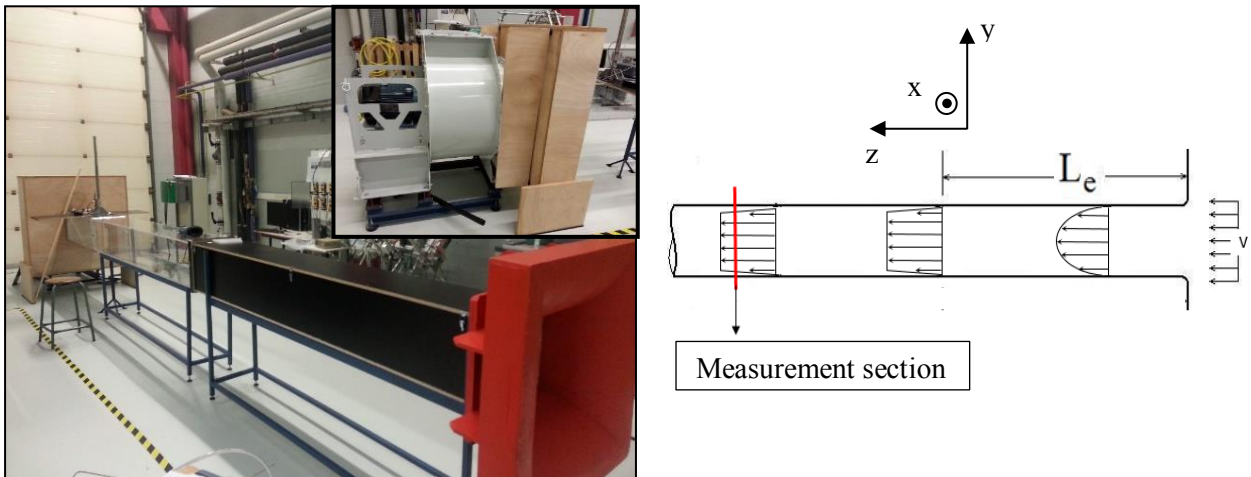


Figure 2 : Test bench and vacuum fan (left); Flow direction and measurement emplacement (right)

0.029 m diameter dummy cables are made of an aluminium core, a ceramic body and two heatshrink polyethylene (PE) outer jackets, the same material that is used for power cables outer sheath. These cables have been instrumented with ten thermocouples (T-type, $\pm 0.5 \text{ }^\circ\text{C}$) placed in grooves at the ceramic surface in a section located at 0.7 m from the cable end. The grooves were filled with ceramic mortar with equivalent thermal characteristics as the cable body. The dimensions (tunnel length and section, cables diameters) have been set to assure a fully turbulent flow at the measurement section. The heat is generated by an alternating current flow up to 600 A through the cables. The current is measured with an instrument transformer ($\pm 0.5 \%$) and the electrical resistivity is measured with a four-point probe method ($\pm 0.25 \% + 25 \mu\Omega$).

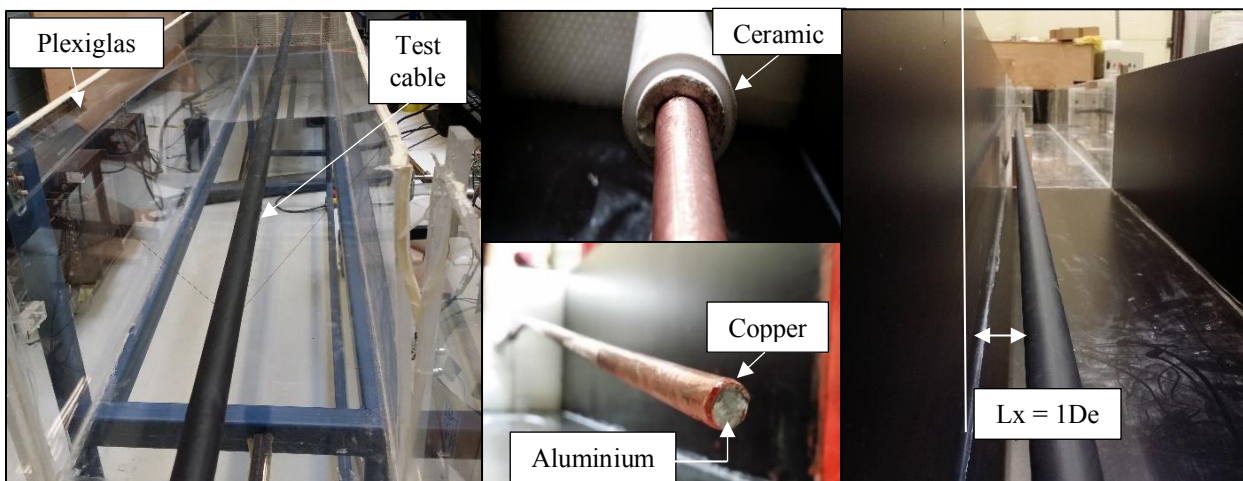


Figure 3: Dummy cable – Centered configuration (left); cable details (middle); near wall configuration (right)

2.2. Test protocol

The single cable configuration has been tested at $Lx = 5.7De$ (middle of the test section) and at spacing values of $Lx = 2De$, $Lx = 1De$ and $Lx = 0.5De$ from the tunnel wall (see Figure 1). The current value (heat generation) is adapted in order to keep the cable at a constant surface temperature whatever the spacing value and the velocity used in the tunnel.

The tests are done at six Reynolds numbers with the air flow generated by a blower functioning on exhaust. A velocity profile at the section used for the measurements has been done by pitot tube for the six flow regime tested. Air temperature and the cable core temperature are monitored respectively by thermocouples type K ($\mp 1^\circ\text{C}$) and type T shielded (to prevent perturbation of the measures by the transiting current).

The local Nusselt numbers are deduced from experimental data by equation (3) below with air properties calculated at bulk temperature

$$Nu_{De} = \left(\frac{De}{\lambda}\right) \frac{P_{conv}}{\pi De [(\theta_s - \theta_{ambient})]} \quad \text{with} \quad P_{conv} = P_{tot} - P_{ray} \quad (3)$$

$$\theta_s = \theta - \frac{1}{10} T_2 P_{tot}$$

where θ is the local temperature ($^\circ\text{C}$). The mean azimuthal Nusselt number are calculated with the ten data points by equation (4)

$$\overline{Nu_{De}} = \frac{De}{2\pi\lambda(\overline{\theta_s} - \theta_{ambient})} \int_0^{2\pi} P_{conv}(\varphi) d\varphi \quad (4)$$

The radiative contribution to the heat transfer is subtracted from the total power for each data points. A 2D numerical simulation using COMSOL Multiphysics® is realized for each configuration. The fast hemicube algorithm is used to compute the view factors, which is advantageously fast to produce an approximate value [7]. The Experimental temperature profiles are used as boundary conditions on the tunnel walls and on the PE-sheat/ceramic interface. The thermal equilibrium is computed and the radiative heat flux is extracted and used to compute the convective exchange.

3. Results and discussions

3.1. Radiative contribution to the heat transfer

The impact of the wall on the cable radiative heat transfer can be observed in the Figures 4. The radiative cooling is decreasing with the spacing value which is explained by two factors: first, the reduced surface with which the part of the cable surface in close proximity with the tunnel can radiate heat. Second, the overheating of the nearest wall facing the cable when the steady-state is reached.

The radiation exchange is then less important with the already hot surface (see wall temperature measurements in Figure 5).

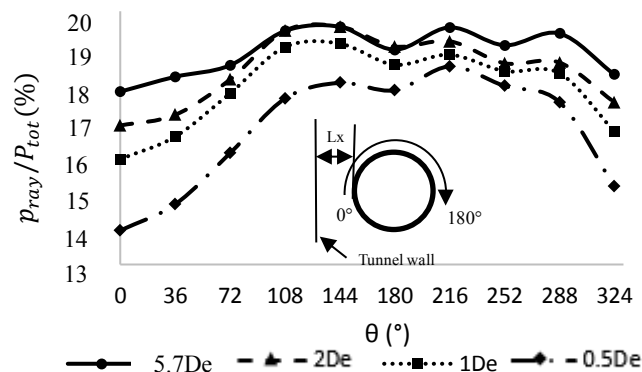


Figure 4 : Azimuthal distribution of the radiative contribution to the total heat transfer
 $- R_{e_{De}} = 2.61 \cdot 10^4 -$

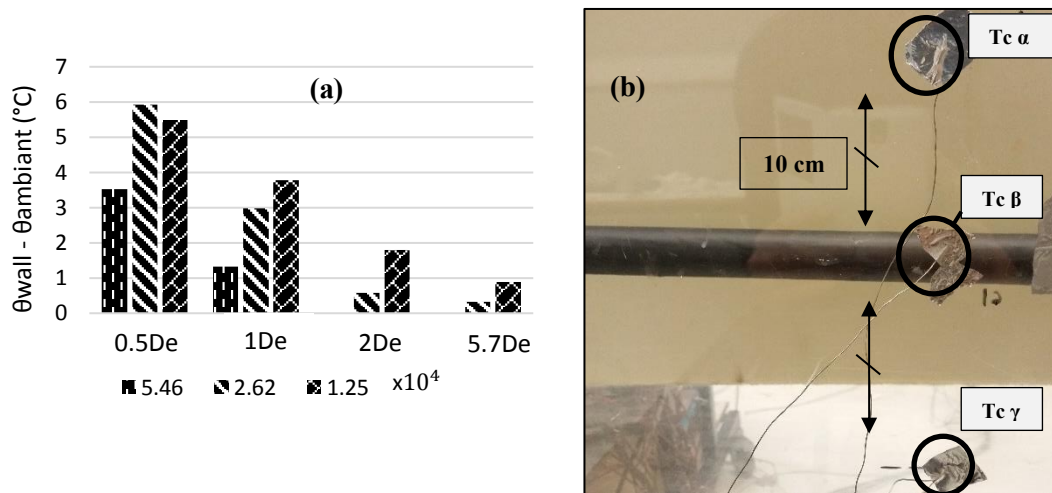


Figure 5: (a) Overheating of the tunnel wall (Tc β); (b) Wall instrumentation

The radiosity method calculation [8] and COMSOL simulations of the radiative exchange between the cable and the walls have shown the radiative losses to be up to 30% of the total heat loss, then decreasing as the Reynolds number rises. These percentages stay fairly constant for every configuration.

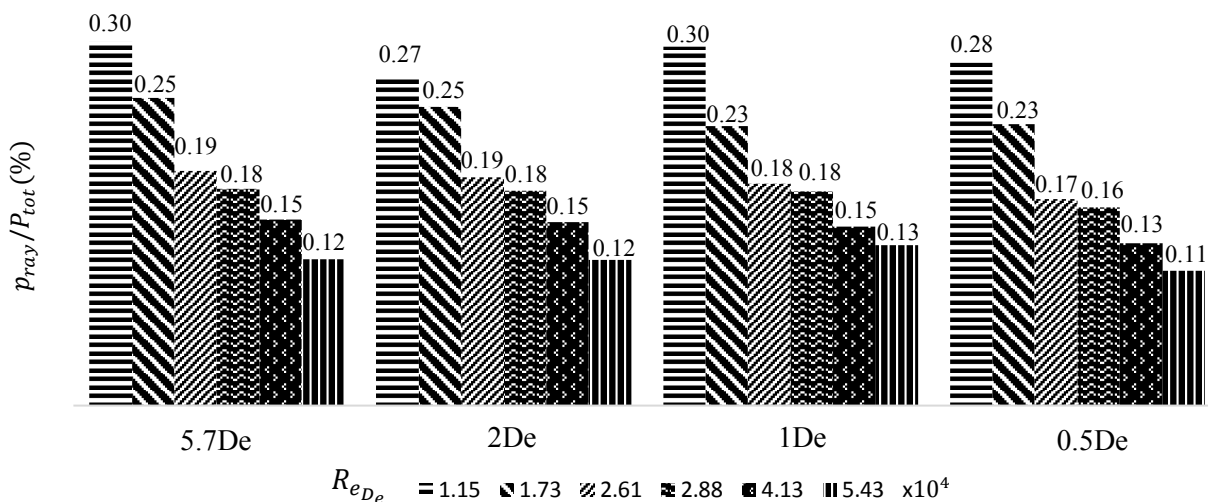


Figure 6 : Radiative contribution to the total heat loss (%)

3.2. Mean azimuthal Nusselt number

The mean azimuthal heat transfer for the three configurations are presented in the Figure 8 below. Nusselt correlations are obtained by power law trend curves and are compared with the power law from [1], first with the given C constant for a single cable ($C = 0.13$), then choosing the constant for the best fit. Measurement uncertainties on the Nusselt values range from 11% to 13%.

The Figure 7 compares the experimental results with the power law proposed by [1]. Nusselt values are found to be meaningfully lower than the ones expected from the correlation. This can be explained by two factors: the difference in aspect ratio, 11.4 in this study, in-between (15.3 – 40) for the correlation presented in [1]. The effect of having turbulent flow without any perturbations from a support and a sufficient length for the thermal boundary layer to develop, thus reducing the heat transfer as the temperature gradients stabilize themselves along the cable length as explained by Pilgrim [2].

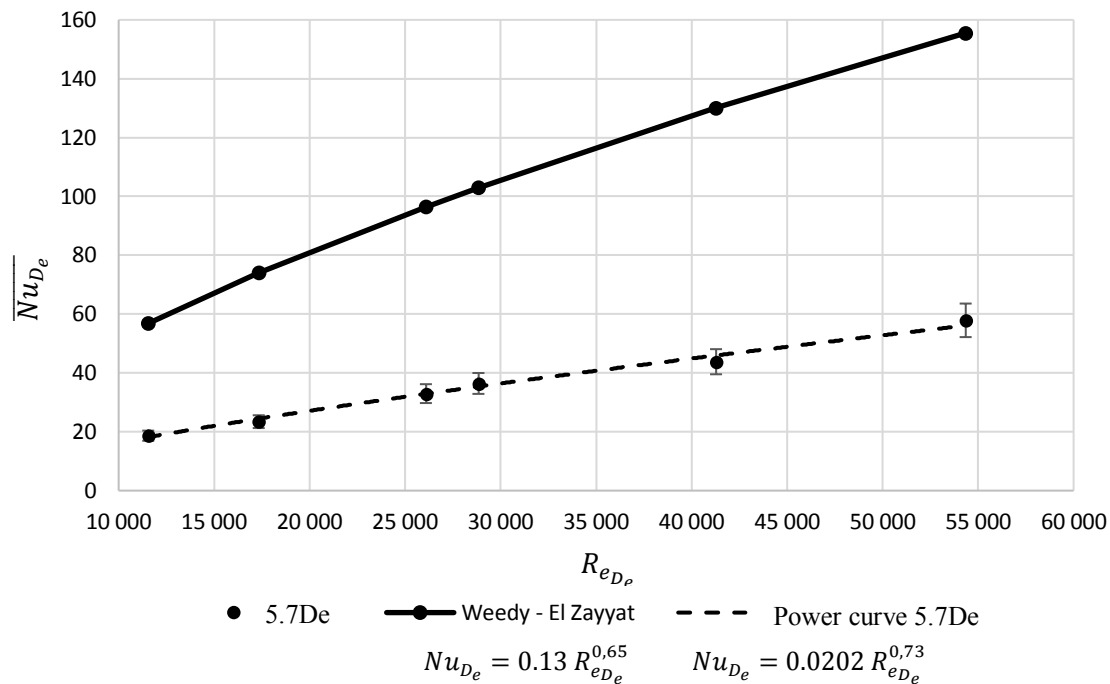
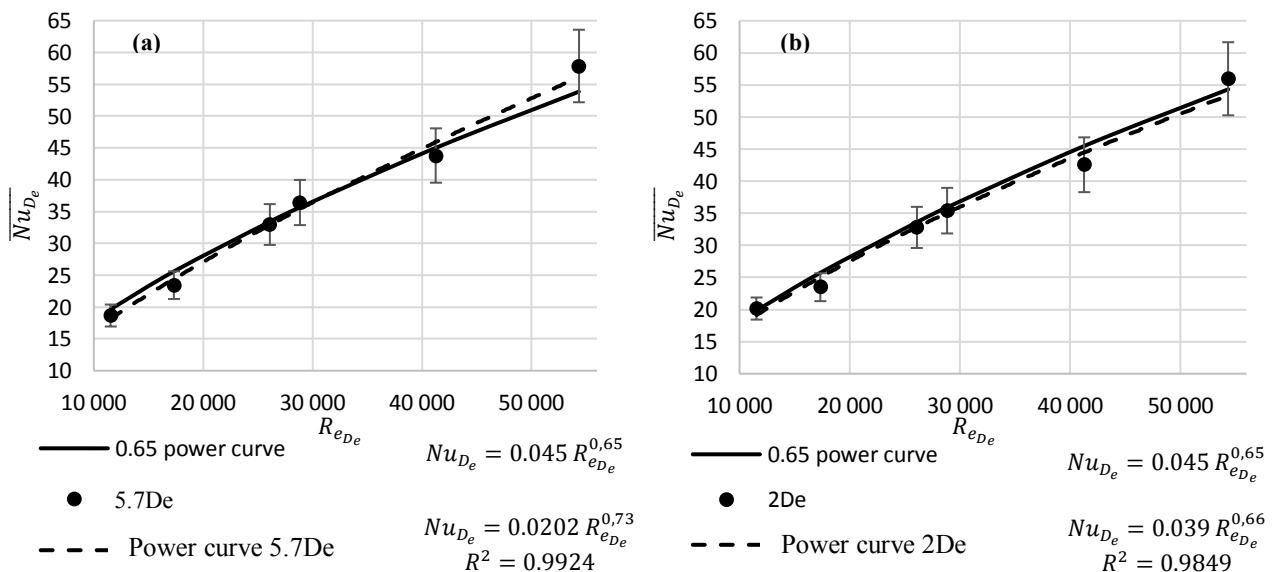


Figure 7 : Comparison of experimental overall Nusselt numbers with [1] – 5.7De cable position –

The kind of power law from [1] can be used to fit the experimental data within the error margins. Below, the Figures present two fitting curves for the experimental data, one based on the correlation of [1] with a constant matching the data, and a power curve fitting curve calculated directly by the least square method. A good match of the correlation of Weedy and El Zayyat [1] is found for the 1De and 2De positions (power of respectively 0.65 and 0.66) but it is far less accurate for the 5.7De and 0.5De as the least square fitting returns power respectively of 0.73 and 0.75.



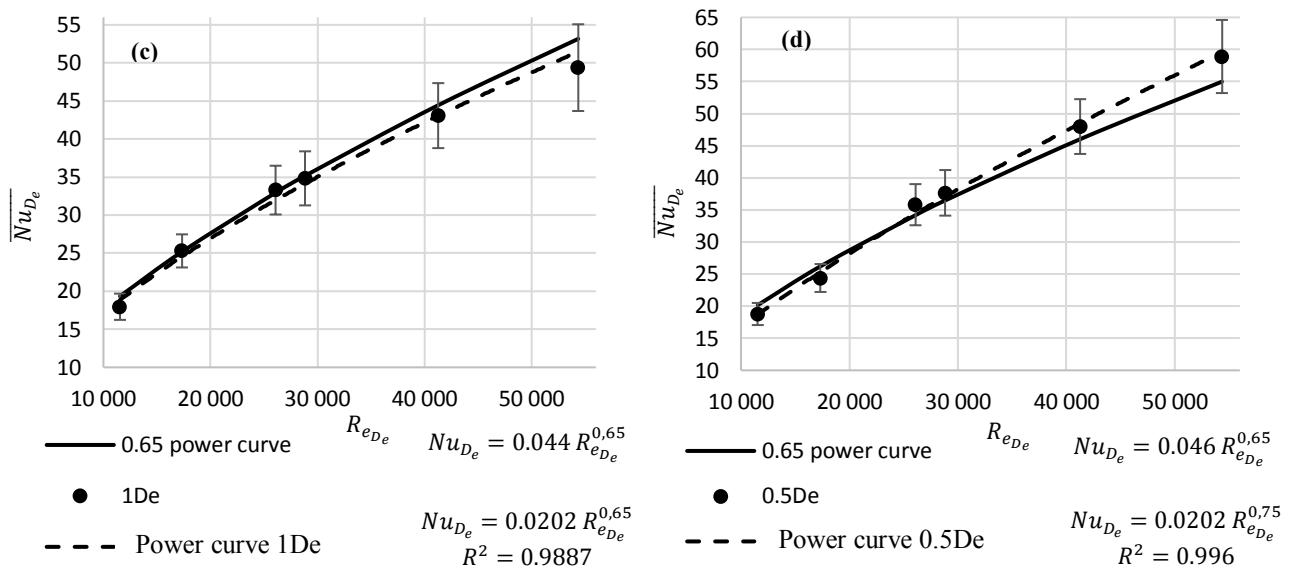


Figure 8 : Mean azimuthal Nusselt number for the single cable configuration
 – (a) 5.7De (middle); (b) 2De; (c) 1De; (d) 0.5De –

The Figure 9 presents the least-square curves-fitting data for all Lx values. No threshold value is clearly found for the mean azimuthal heat transfer even if a slight decrease of the Nusselt curves can be observed for 2De and 1De. The higher levels observed for the 0.5De position is within the uncertainty margins of the 5.7De curve. The heat transfer for the 0.5De position is still superior in comparison to 2De and 1De positions.

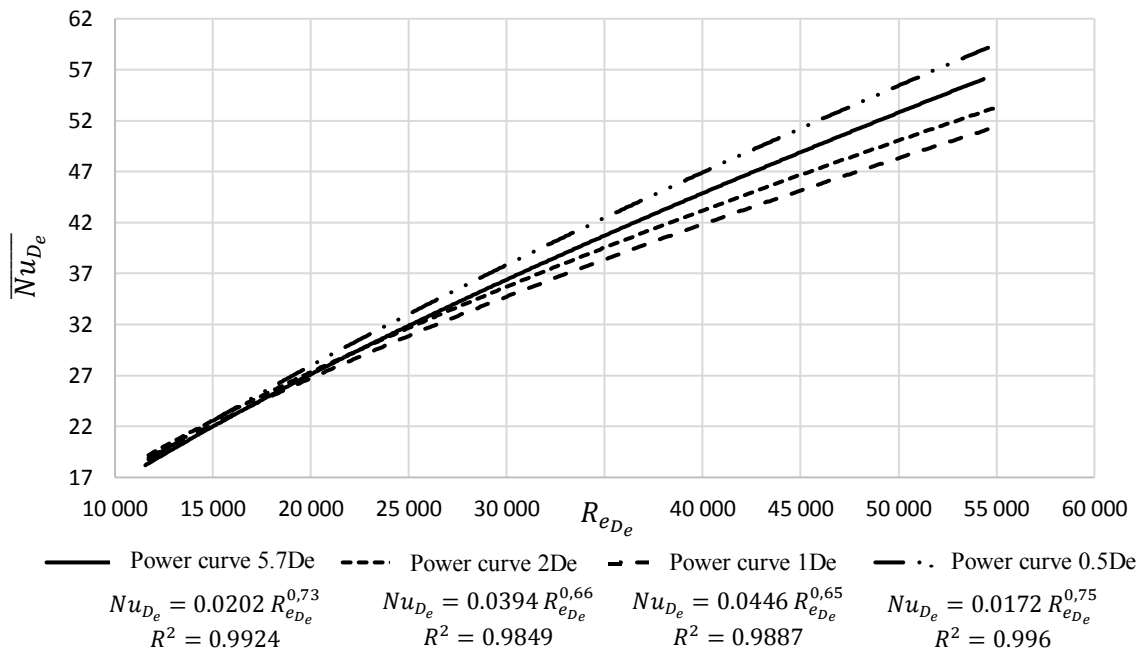


Figure 9 : Overall Nusselt number for the single cable configuration
 – Lx = 5.7De, 2De, 1De, 0.5De –

4. Conclusion

The forced convection over long cylinder surfaces has been studied and compared with the existing empirical model made for a single cable configuration. No clear threshold value for thermal independency is found as in [1] but experimental data showed an overestimation which can be accounted for the particularity of the experimental setup used in [1], those being an undeveloped turbulent flow and the presence of racks for supports. The effect of the wall spacing has also shown a cooling profile that cannot be accounted for with the sole forced convection, which led to an investigation of the radiative heat transfer contribution of the cable portion facing the closest tunnel wall. A rise in the temperature of the tunnel wall has been found while the other walls stay close to room temperature and the radiative contribution to the heat transfer has been found to be significant.

A more complete radiative study of the experimental configurations is currently under way involving measurements for the radiative heat flux of the cable. Several other cable configurations, involving two and three cables are studied to assess the impact of a cable group on the cooling profiles.

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