A THERMAL STUDY OF POWER CABLES COOLING IN TUNNELS

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SOMMAIRE

I. INTRODUCTION

II. EXPERIMENTAL & SIMULATION SETUP

III. CABLE COOLING : RESULTS & DISCUSSION

IV. IMPACT ON THE MAXIMUM PERMISSIBLE CURRENT

V. CONCLUSIONS
I. INTRODUCTION
   I. Power transmission network
   II. Thermal limiting factor
   III. Simulation challenges

II. EXPERIMENTAL & SIMULATION SETUP

III. CABLE COOLING: RESULTS & DISCUSSION

IV. IMPACT ON THE MAXIMUM PERMISSIBLE CURRENT

V. CONCLUSIONS
I – POWER TRANSMISSION NETWORK

- From energy production centers to the distribution networks, several solutions are available:

**Overhead lines:**

**Buried lines:**

**Tunnels:**

Exemple of London tunnel.
I – THERMAL LIMITING FACTOR

- Principal limiting factor: the dielectric insulation temperature.

- The Joule heating from the transiting current is dissipated through:
  - Conduction in the cables layers.
  - Convection with the surrounding air.
  - Radiation with other surfaces (tunnel walls, other cables, etc.).

- Existing rating methods suffer some limitations such as:
  - All cables are considered identicals.
  - Empirical derating coefficients for groups.
  - Cooling laws not proposed for fully developed turbulent flow.

Ph.D. main objective: Remove the last two issues
I – SIMULATION CHALLENGES

- Tunnels are kilometers long…
  - Long geometries involved

- High aspect ratio between the tunnel and the cables
  - High number of elements for a good mesh quality.

- Need of a Low Reynolds approach for high precision in the computed heat transfer.
  - Even higher number of elements…

- Turbulent flow regime needs a (very) long entrance length.
  - More elements…

![Graph showing heat transfer coefficient evolution with Reynolds numbers Re = 11600 and Re = 26220 over distance z (m).]
I. INTRODUCTION

II. EXPERIMENTAL & SIMULATION SETUP
   I. Ventilated cable tunnel Mock-up
   II. COMSOL use for data treatment
   III. 3D numerical simulations

III. CABLE COOLING : RESULTS & DISCUSSION

IV. IMPACT ON THE MAXIMUM PERMISSIBLE CURRENT

V. CONCLUSIONS
II – VENTILATED TUNNEL MOCK-UP

Measurement section

6.5 m

Inlet

Plexiglas

Test cable

Lx = 1De

Copper

Aluminium

Ceramic
The experimental data are treated with a coupled MATLAB-COMSOL inverse method.

The local Nusselt numbers $Nu_i$ are obtained with an optimization script using two parts:

The COMSOL heat transfer module for the heat transfer resolution.
- 2D geometry.
- Heat conduction in the cables & tunnel walls.
- Surface-to-surface radiation (hemicube formulation).
- Heat transfer coefficient at the cable surface controlled by the optimization process in the MATLAB interface.

The mesh is a very fine one
- Underconstrained model.

Use of an interpolation fonction for the heat transfer coefficient

$\frac{h_{ambient}}{10 \, W.m^{-2}.K^{-1}}$

Iterative heat transfer coefficient

Control point for the optimization method

0.029 m
The local Nusselt numbers $Nu_i$ are obtained with an optimization script using:

- A MATLAB optimization process based on the minimization of the $S$ criterion (1).
  - A second order regularization is chosen.
  - The regulation coefficient $\beta$ is optimized for each iteration.

$$
S = \sum_{i=1}^{10} (\theta_{\text{comsol}} - \theta_{\text{mes}})^2 + \beta \sum_j (h_{j+1} - 2h_j + h_{j-1})^2 \quad (1)
$$

- The mean Nusselt number is obtained by integration on the cable surface.

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

Cooling profile identification process:

- Initial heat transfer coefficient vector $h_0$ and $\beta_0$ value
- Optimization script
  - $h_\varphi = h_{i,\text{opt}}$
  - $\beta = \beta_{\text{opt}}$

LiveLink™ for MATLAB®
- 2D COMSOL simulation with the profil $h_\varphi$ at iteration $i - 1$
- Extraction of the $\theta_i$ and $h_i$ simulated data
- Evaluation of the $S$ criterion (1)

Final result: $h_i = h_\varphi$
The validation case led to a benchmark with the opensource code OpenFOAM and experimental published results.

- Similar results obtained.
- OpenFOAM finite volume formulation preferred to COMSOL for the 3D multi-million mesh elements (cluster availability).
II – 3D NUMERICAL SIMULATIONS

- Simulation RANS using the open source code OpenFOAM.

- Coupled solver and low Reynolds mesh with a turbulence model k-omega SST.

- \( Y^+ << 1 \)
I. INTRODUCTION

II. EXPERIMENTAL & SIMULATION SETUP

III. CABLE COOLING : RESULTS & DISCUSSION
   I. Airflow analysis & cable cooling profile
   II. Mean Nusselt numbers
   III. New cooling laws

IV. IMPACT ON THE MAXIMUM PERMISSIBLE CURRENT

V. CONCLUSIONS
III – AIRFLOW ANALYSIS & CABLE COOLING PROFILE

- As the cable wall spacing decreases, the air flow structure deforms itself.
- A velocity drop is observed in the gap between cable and wall.
III – AIRFLOW ANALYSIS & CABLE COOLING PROFILE

- The observed velocity drop can be down to 50% of the entrance velocity.
- A threshold wall spacing value of $L_x = 2D_e$ can be defined.

![Diagram showing velocity profile line plot at $z = 2.8\,\text{m}$, constrained and unconstrained regions, and cable.]

![Graph showing $U_z/U_0$ vs. $x/L_x$ for different $L_x$ values.]

- The observed velocity drop can be down to 50% of the entrance velocity.
- A threshold wall spacing value of $L_x = 2D_e$ can be defined.

![Graph showing $N_{Re}$ vs. $\alpha$ for different $L_x$ values.]

$\alpha = 10^\circ$

$Re_{De} = 26220$

$L_x = 5.7D_e, L_x = 2D_e, L_x = 1D_e, L_x = 0.5D_e$

- Experimental $L_x = 0.5D_e$

$Re_{De} = 26220$
III – MEAN NUSSELT NUMBERS

- The depreciation of mean Nusselt number is clearly obtained, with a 20% drop for very close proximity with a wall (Lx = 0.5De).
- Heat transfer 2 times less important as regards to the current cooling law [1].

Possible reasons:
- Turbulence entrance length not reached in [1].
- Studies without support elements (brackets).

\[ \bar{Nu}_{De} = 0.13 R_{eDe}^{0.65} \]

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II. EXPERIMENTAL & SIMULATION SETUP

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IV. IMPACT ON THE MAXIMUM PERMISSIBLE CURRENT

V. CONCLUSIONS
IV – IMPACT ON THE MAXIMUM PERMISSIBLE CURRENT

- Using the design tool for underground power cables with the new laws, the impact on the maximum transmissible current in the power link can be tested.
- Idealized case (no brackets, no corkscrewing effects, etc.)

Max. operating temperature: 90°C in the core

<table>
<thead>
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<th></th>
<th>Weedy and El Zayyat</th>
<th>$N_u De (L/x/De)$</th>
<th>Weedy and El Zayyat $I = 2354,A$</th>
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<td>h wall (W/m².K)</td>
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<td>h cable (W/m².K)</td>
<td>9,35</td>
<td>3,96</td>
<td>9,37</td>
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<td>I max (A)</td>
<td>2526</td>
<td>2354</td>
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V - CONCLUSION

- Experimental & numerical studies have highlighted the impacts of the proximity to a tunnel wall and the flow development.
  - The depreciation of the heat transfer can be of 20% for close installations to a wall.

- On-going work.
  - Cable groups effects on the heat transfer (two cables and trefoil configurations).
  - Effects of the support elements.

- Wish list
  - Get rid of the OpenFOAM platform for the 3D ➔ have COMSOL simulate everything.
  - A mean to simulate details local heat transfer for very long geometries with limited mesh elements (ideas ?).
  - Or else, a full COMSOL cluster license…
THANK YOU

ANY QUESTIONS