The Fifth International Conference on Railway Technology
RAILWAYS 2022
22–25 August 2022
Montpellier, France

Proceedings of the Fifth International Conference on
Railway Technology:
Research, Development and Maintenance
Edited by J. Pombo
Civil-Comp Conferences, Volume 1, Paper 28.2
Civil-Comp Press, Edinburgh, United Kingdom, 2022, doi: 10.4203/ccc.1.28.2

Dynamic coupling between convective cooling and power losses: Application to train electronic systems

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Abstract

The recent progress obtained with silicon carbide on the performance of electronic systems has opened possible improvements on the cooling system. Instead of using forced cooling, the possibility of passive cooling is investigated, which would reduce the size and weight of the cooling system on trains. This study focuses on the unsteady coupling between the flow past a flat plate and the flux input heating the flat plate. This coupling impacts the temperature response at the interface and is of significant interest regarding the cooling of electronic systems on trains. With the use of two driving behaviours corresponding to two classical phases of train in operation, the interaction between the heat flux and the flow is investigated via two methods. These two driving behaviours are simplified versions of a constant speed phase, with constant losses, and an acceleration phase. An integral method is applied for a laminar incompressible flow to get the temperature evolution over time at different locations on the flat plate for these two cases. CFD simulations for a laminar flow are carried out and compared with the results of the first method. For the first driving behaviour, the agreement is good in the first half of the flat plate considered between the two methods. The differences are more important in the second half. This could be explained by the assumptions made on the boundary layer development. Regarding the acceleration phase, the peaks are well captured, and the match is very good in the temperature evolutions in the first half of the plate.

Keywords: passive cooling, power electronics, losses, coupling, CFD, integral method

1 Introduction

With the significant improvements on electronic systems over the past few years [1], the possibility of simplifying the cooling system has been considered on recent developments of trains, especially with the recent progress on Silicon carbide. These systems consist of power electronic components that convert the electric current from the catenary and the transformer into an adequate current for supplying the electric motor. The Japanese high-speed train has, for example, recently tested replacing its active forced cooling system to a passive one [2], where the action of the running flow beneath the train is used to cool down the electronic components, mounted on a circuit on top of fins. Depending on the driving cycles of the train, the electronic system may be undergoing more losses while the speed of the train may be low to cool it down efficiently in a passive way.

The coupling of the convective flow with the electronic components can be modelled by a fluid/solid thermal interaction. This kind of problem is referred to as a conjugate heat transfer problem (CHT) [3]. Numerically, the challenge to use computational fluid dynamics (CFD) simulations on three-dimensional configurations is big. The reason lies in the difference in time scales between convection and conduction [4]. These coupled simulations are expensive, and one needs to resort to simplifications. On the modelling side, CHT problems still require more understanding. They have been largely dealt with in the literature, under certain conditions, but studies on the unsteady coupling of both is far more seldom and is yet important for the prediction of the temperature [5].

The objective of this work is to investigate the application of a simple integral method for the prediction of the wall temperature considering realistic signals for the speed and the power losses over time for a train. Two simplified driving behaviours are considered in this study. One corresponds to the case where the electric motors only compensate for the air resistance (constant traction force and speed). Another corresponds to an acceleration phase and a constant speed. This is done on a simplified configuration: a flat plate heated by an unsteady heat flux is cooled down by a laminar flow of constant freestream temperature and variations on the freestream velocity are considered. The freestream velocity remains low for this work to comply with the laminar flow assumption. The results from this method are also compared to the predictions from CFD simulations in laminar conditions.

2 Methods

The configuration studied for the case is showed in Figure1. It consists of a flat plate, of length a, heated by a time-varying heat flux. The integral method as it is applied here derives from Lachi *et al*'s study [6], that uses Karman-Pohlhausen's method (KP method) [7] to estimate the difference along the plate over time.

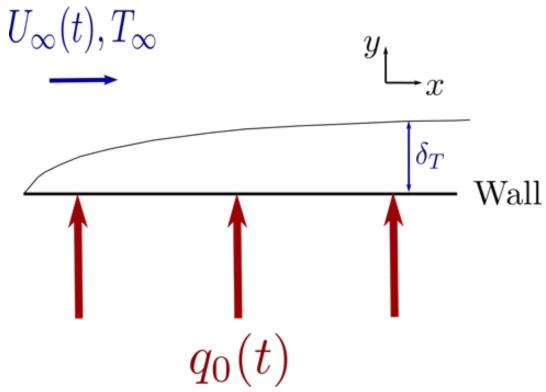

Figure 1: Case study for the unsteady coupling.

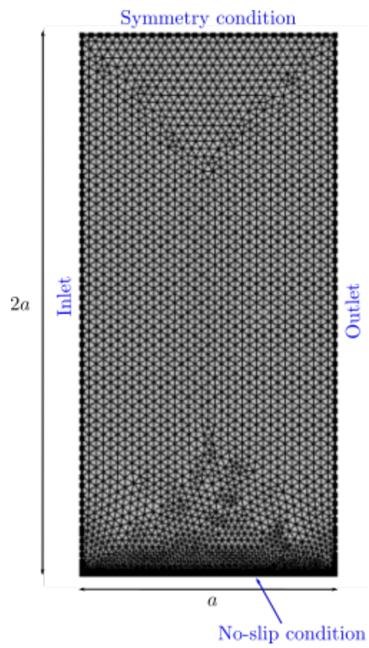

Figure 2: Screenshot of the grid used in COMSOL, also indicating the different boundary conditions.

The basic idea is to write the temperature profile (resp. the velocity profile) as a polynomial within the thermal boundary layer of thickness δ_t (resp. boundary layer of thickness δ). If the temperature difference is denoted $\Theta = T - T_\infty$, the method assumes that Θ is a fourth-degree polynomial of $\frac{y}{\delta_t}$. By doing so, δ_t can be expressed as a function of $\Theta_\mathrm{w} = T_w - T_\infty$, which leads to a partial derivative equation on Θ_w that can be numerically integrated using a first-order upwind scheme in space and time. Indeed, this leads to the solving of a polynomial, whose corresponding roots are selected using Sturm's procedure [8]. The numerical process can simply be written in Python.

Regarding the CFD, the software used is COMSOL [9]. The simulations are done in laminar conditions with a timestep controlled by the solver, using a backward differentiation formula (BDF) [10]. The mesh consists of 5000 vertices and the simulation runs within a few minutes. The boundary conditions used are classically based on the freestream conservative values of Navier-Stokes equations at the inlet, a static pressure at the outlet, a no-slip condition at the wall and a symmetry condition a t the top of the fluid domain, as indicated in Figure 2.

The two methods are applied to two cases, representing simplified driving cycles of a train in operation. The idea is to analyse the transient part on how the wall temperature develops:

(i) Constant speed and power losses. This happens when the train motors drive the train with a constant tractive power on a railway track with no elevation. The speed and the losses are here constant over time. The speed is $U_\infty = 1\ m/s$ and the heat flux $q_0 = 100\ W/m^2$. With air, the corresponding Reynolds number is $Re \approx 6000$.

(ii) Constant acceleration before reaching the speed aimed for. This corresponds to a ramp on the speed with a constant power loss. The latter decreases by half once the constant speed has been reached. Here, the speed is increased from $U_\infty = 0$ to $1\ m/s$.

The two cases are illustrated in Figure 3.

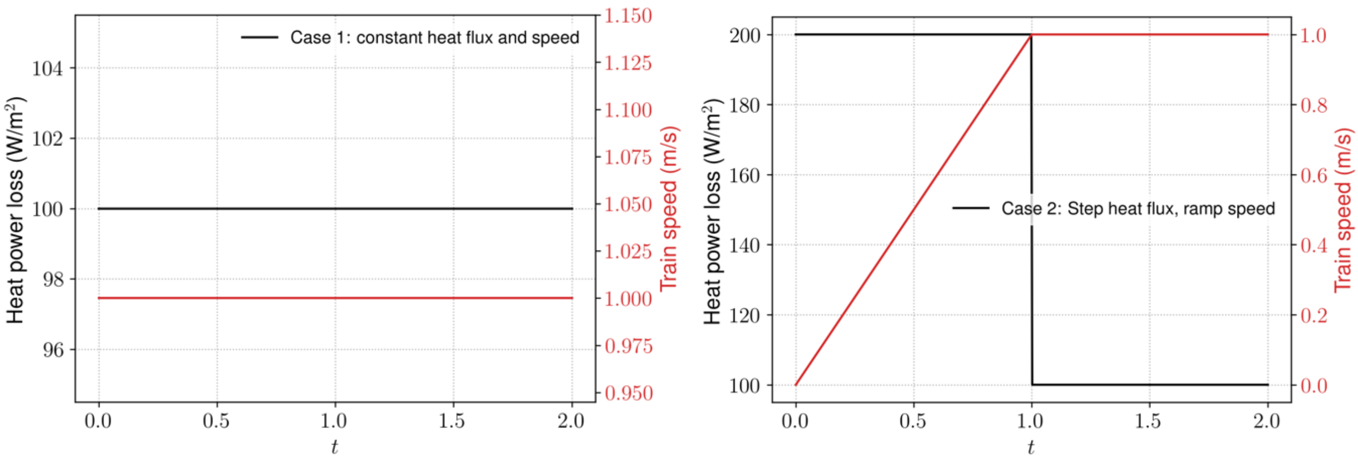

Figure 3: Signals used for the study corresponding to the (a) constant heat flux and speed (b) acceleration phase of the train.

3 Results

Case 1: Constant heat flux and speed

Figure 4 shows the temperature at the wall at different positions of the flat plate of length $a = 10\ cm$, comparing the results from the integral method and CFD. Let us first compare the levels reached in the steady regime. The fit in the first half of the plate is quite good: the integral method overestimates the wall temperature obtained from the CFD but stays within $1°C$. Moving farther downstream, an increase in temperature can be noted. Indeed, because the heat flux is applied all along the flat plate, the temperature keeps rising streamwise. The difference between the KP method and CFD is larger in the second half of the plate.

Regarding the transient, between 0 and $0.2s$, the tendency is the same: the temperature increases in the first one-tenth seconds until a plateau is reached. Compared to CFD, the transient part is shorter in all cases, meaning that the steady temperature is reached more quickly.

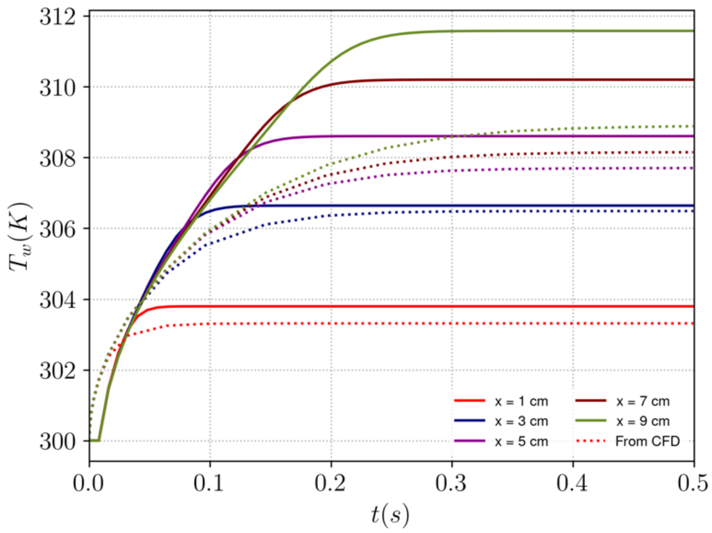

Figure 4: Temperature evolution at the wall for case 2. Solid lines represent the temperature response from the integral method.

Case 2: Constant acceleration

With the constant acceleration, the assumption of a constant freestream velocity is not valid anymore. Figure 5 shows the evolution of the wall temperature as a function of time. During the acceleration phase, until $t = 1s$, two phases can be distinguished in both the CFD and the integral method: one where the temperature increases and a second where it starts decreasing. The existence of a peak is noted during that phase corresponding to the moment where the speed compensates the heat flux input in terms of cooling. After that peak, the decrease starts because the speed is large enough to cool down the flat plate. When the speed reaches $1\ m/s$, the power losses are reduced by half. In the temperature response, a discontinuity is observed

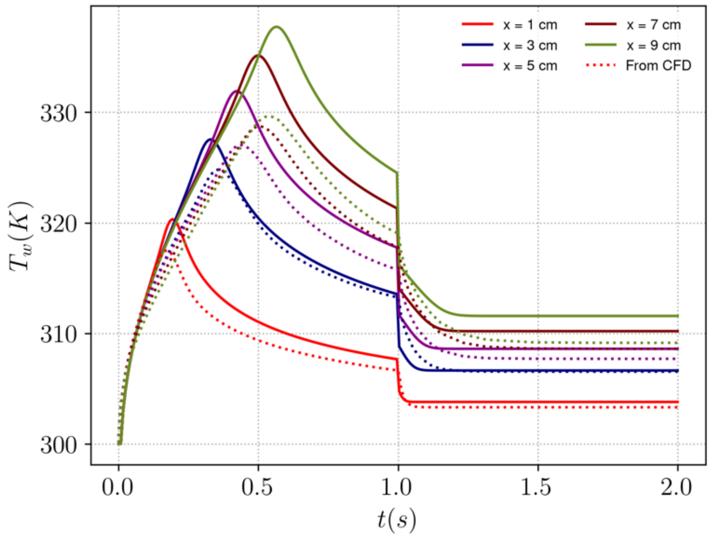

Figure 5: Temperature evolution at the wall over time for case 1. The solid lines represent the temperature response from Kalman-Pohlhausen's method.

corresponding to that of the step signal. The temperature of the wall continues its descent to finally reach a plateau within a few one-tenth seconds, a transient duration that corresponds to case 1.
Regarding the comparison between the CFD and the integral method, the fit is good for the upstream part of the plate: the peak is well captured by the integral method, slightly delayed compared to the CFD. The temperature difference stays within $2°C$. Farther downstream, the temperature computed from KP method overestimates the peak, especially in the second half of the plate. This difference is however still reasonable, and the peaks are well captured.

4 Conclusions and Contributions

The investigation of Karman-Pohlhausen's method on two driving behaviours of a train in operation confirms the interest of that kind of method for predicting the wall temperature when accounting for the coupling of a convective flow cooling down a plate heated by an unsteady flux. This is compared to a laminar simulation carried out on COMSOL.

For the first driving phase, KP method and CFD show a good agreement for the first half of the plate. For downstream positions, it seems that the efficiency of cooling is underestimated by the analytical method. A further analysis is needed to explain this behaviour by comparing the boundary layer development at different positions between the two methods.

In the second case, the freestream velocity is varied and increased during the acceleration phase. It fits well in the first half of the plate with the CFD, capturing the good location and level of the peak on the temperature. This is a novelty in the way the method has been used since the freestream velocity is assumed to be constant in that kind of integral methods. Extending this to a slightly varying freestream velocity seems to be well-adapted but it requires a further investigation to quantify the validity of that extension.

Future work concerns the validity of that method for larger speeds with a more detailed analysis on the boundary layer. The assumption has also been made on a laminar flow. That type of integral is indeed much more complex to apply to turbulent flows since the velocity fluctuations need to be accounted for. Finally, the extension to more realistic geometries should be investigated, for example by considering a thick two-dimensional problem with a slab cooled down by a convective flow past it. The extension to actual 3D geometries requires more work on the estimate of a thermal impedance modelling the heat sink, consisting of the electronic systems and fins to maximize the heat transfer between the circuit and the fluid. For designers, the latter objective could help gain a lot of time in the design process before using heavy CFD simulations.

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