Power Electronics Packaging for In-Road Wireless Charging Installations

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***Abstract*—When power electronics are deployed under the road surface as part of a wireless system it is important to know that their packaging provides adequate heat extraction as well as the required environmental protection – often conflicting requirements. Presently very little can be found in wireless charging standards and literature on the topic of thermal modelling for in-ground components. Yet, this is a topic of great practical significance especially for in-road systems. Traditional cooling methods are not readily applicable underground. This paper uses finite element thermal modelling to investigate the cooling of a representative medium-power in-road wireless system, housed in a sealed ground assembly (GA) chamber and installed to UK requirements (HAUC). The paper quantitatively compares design options and provides practical recommendations for in-road installation thermal management.**

***Keywords*—vehicular and wireless technologies, inductive charging, thermal analysis, standards, thermal engineering, soil properties**

I. Introduction

In the transition towards a low-carbon economy, electric vehicles (EVs) have the advantages of lower carbon dioxide emissions at the tailpipe, overall improved operational simplicity and improved driver experience. Moreover, modern EVs boast increased mileage per single charge and the "range anxiety" barrier is no longer the leading concern for new EV owners. It is being replaced by the lack of sufficient charging infrastructure along with the duration and inconvenience of charging [1]. Commonly mentioned issues associated with plug-in charging include the physical effort of handling heavy cables, expertise required to use appropriate cable connectors, ensuring cables do not become a trip hazard especially if the car is parked in a public place, etc. Additionally, many car users do not have dedicated off-street parking and would need daily access to public charging points. Although still in short supply, installations of regular charging points on-street (as opposed to in purpose-built charging hubs) are already adding significantly to the street clutter problem.

One potential solution to the above issues is the adoption of in-road wireless charging systems. High-frequency inductive power transfer between magnetically coupled transmitter ground coils and receiver vehicle coils allows wireless charging across the air gap between the underside of the car and the road surface (100 – 300 mm). Modern wireless charging technology has reached high efficiencies (80% – 93%) comparable to plug-in charging [2]. With the adoption of advanced power electronic components and precise alignment techniques, the efficiency of wireless charging may increase even further to 95% and above.

Wireless charging technology can offer charging opportunities in a wide range of use cases: on-street parking bays, public car parks, semi-dynamic opportunity charging for taxi ranks, even dynamic charge-on-the-move. A ubiquitous technology able to adapt to universal standards and requiring minimal human interaction would be a valuable solution. However, this it is still in its infancy with strategic, conceptual and design challenges yet to overcome.

Closely coupled inductive charging is not unfamiliar to the public in smaller consumer electronic devices (e.g. toothbrushes, smartphones). Wireless EV charging applications require not only a larger practical distances for the power transfer but also larger power levels (3 – 11 kW for static charging, 20 – 300 kW for opportunity and dynamic charging) that can match modern EV fast charging capabilities. The introduction of wireless charging has seen public concerns about safety, operation and environmental impact, but it is also seen as desirable in terms of minimising human effort, facilitating prospective EV owners with disabilities and can reducing visible infrastructure.

In wireless charging related literature the focus so far has been very much on design, modelling and reporting of coils and power electronic circuits, but very little has been published on thermal and other practical issues associated with installation of wireless systems in the road. Some very recent work considers the thermal modelling of wireless pads [3], [4]. However, this paper considers the full system including the pads and power electronics, modelling the complete in-road ground assembly (GA) and surrounding ground.

II. Technology Challenges

For on-street opportunity charging and car-parks, integrating the transmitting coil and power electronics in a single in-road assembly or GA is beneficial. However, this means increased potential exposure of sensitive electronics to contamination, shock, vibration and thermal extremes. The GA consists of a power supply and control system (power electronics), an electromagnetic assembly (wireless pad) and protective mechanical structures. The UK's Code of Practice for the Reinstatement of Openings in Highways (HAUC) gives rules for the dimensions, materials, processes and condition for retrofitting the GA [5].

The ground assembly will be installed into the road with a hole at least 50% larger (see Fig. 1) than the protective mechanical structure, onto a concrete pad with a soak-away, and lined with pebbles and concrete. The power cable access duct will enter the structure from underneath. The road surface is made good with backfill as illustrated in Fig. 2 and then

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vibration tamped, and the road surface finished with asphalt as shown in Fig. 1. Whilst this repair restores the road surface and gives a robust foundation, the contents of the GA can still be exposed to contamination, vibration and thermal extremes.

Fig. 1. A photograph of an installed wireless charging GA with approved roadway restoration completed and ready. Credit: char.gy

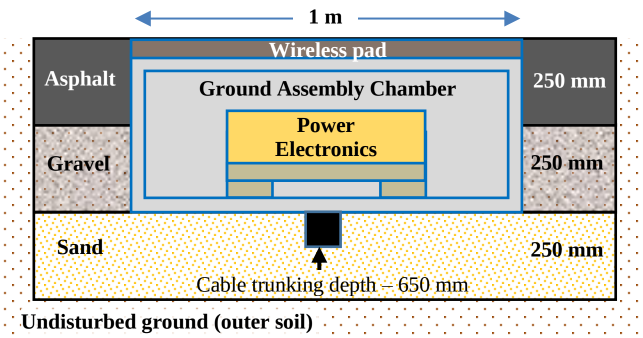

Fig. 2. HAUC compliant installation cross-section of a GA Chamber.

A. *Environmental Protection from Contamination Ingress*

The principal contaminants for a road installation include solids such as dust and debris from brakes, tyres, asphalt etc. (3µm average size), road gritting treatments, ultrafine nano-scale particles from combustion; liquids such as water (rain and flood) and oil splashes; and potentially above-normal concentrations of gasses such as water vapour, NOx and CO_2. The main packaging challenge for in-road wireless charging GAs is to ensure such contaminants are prevented from entering or accumulating within the power electronics chamber as they may cause electrical failure. For this purpose it is assumed that the GA chamber will likely have an ingress protection rating of IP67 or higher so there is no air or liquid exchange between the enclosure and the outside.

B. *Vibration and Shock*

On-street, the GA will be installed at least 500 mm from the kerb, and is therefore subjected to shock and vibration from traffic. There will be significant ground pressure loads applied to the coil pad from heavy vehicles. The BS EN 124 standard sets a static test load of 400 kN for manhole covers in roads. Additionally, there will be dynamic loads exciting the natural frequencies of the structure and any sensitive items inside with worst case shock expected to be caused by the heaviest axle load travelling at the highest speed (60 mph or 96 km/h). The GA's power electronics must be able to withstand such repeated transmitted shocks without damage or early degradation. These sensitive assemblies need to be studied as a suspended item within the enclosure also taking into account the supporting substrate elastic properties.

C. *Thermal management*

With the GA installed into the road, the assembly is subjected to internal and external heat sources and external cooling. In the UK, the road surface temperatures range from -25 °C to +50 °C, due to weather and solar radiation [6]. In-ground temperatures will be more stable due to the large thermal time-constant of the ground.

Careful thermal design is necessary to ensure that component parts' individual temperature limits are not exceeded, which would push them outside their safe operating point. This will protect against premature degradation leading to system failure or damage to surrounding materials, including chemical and physical changes such as polymer post-cure modulus changes, accelerated ageing etc. If components are changed to tolerate higher operating temperatures, the system might be more costly, require more maintenance or may have less benign failure modes and subject surrounding materials to the effects of repeated thermal expansion and contraction. For large scale deployment, cost is also key. There is a system design optimum that requires careful balancing of these conflicts. The use of comparative thermal analysis in this sense is necessary to select the solutions that provide the optimum balance between design requirements.

III. Thermal Modelling

A. *Modelling Approach and Initial Thermal Model*

In a wireless system GA, the two main sources of losses are the power electronics (including the resonant circuit) and the wireless pad. Both these heat sources are included in the thermal model. Power losses within the modelled GA are targeted to be relevant for low to medium power systems (3 – 10 kW). The loss distribution for a 10 kW system published in [3] is taken as a reference here and is in general agreement with other published literature [7], [8] as well as our own experience. Within a wireless system, [3] apportions 75 % of a wireless system power loss to the ground side. Furthermore, within the ground side 60 % of the total GA losses are apportioned to the wireless pad and 40 % to the power electronics.

Thermally-representative models of the power electronics and wireless pad have been included in the model, and total power loss within the GA was apportioned as described between these two components. For example, for a 10 kW system operating at 90 % efficiency the total GA loss is 750 W which is made up of 450 W in the wireless pad and 300 W in the power electronics.

A ground chamber of dimensions 1 x 1 x 0.5 m, sized for low-medium power installations, is modelled here. The wall of the chamber is 25 mm thick for structural support. Support ribs are not anticipated to play a significant role in the thermal performance of the chamber and have not been included here.

The power electronics is modelled as a box (with nominal dimensions 0.5 x 0.3 x 0.2 m) of which the lower 50 mm is an aluminium heatsink. For modelling purposes, the heatsink is treated as a solid block and losses in the power electronics are modelled as a uniform heat generation within the heatsink. A thermally-representative wireless pad is modelled, 50 mm tall consisting of layers of potting compound, ferrite and an aluminium back-plate which is shared with the top of the GA. Power loss within the wireless pad is evenly distributed between the ferrite and potting compound layers.

The ground back-fill layers are modelled according to the HAUC-compliant configuration shown in Fig. 2, with data from a survey of literature sources used for the thermal properties. Surrounding the excavated hole, a generic ground material was used with thermal properties set to those typical of the soil in the UK.

In the initial thermal model, the GA chamber wall material was aluminium, selected for its high thermal conductivity relative to the surrounding ground and thereby the ability to distribute heat into the ground over the full contact area. The power electronics heatsink is connected to the bottom of the chamber by aluminium feet which assist the transfer of heat. This configuration is analysed to understand the thermal performance under different environmental conditions and thereby gain insight into the thermal aspects of in-ground installations, including an appreciation how much heat can be practically dissipated from within an in-ground GA chamber. The initial configuration was then modified and additional models computed to further examine the choices of chamber wall material, power-electronics mounting location and different mechanisms for heat transfer between the power-electronics and chamber wall.

Material properties and environmental conditions used for the initial model are listed in Table 1. In later sections, some of these parameters are varied as described in those sections. Three-dimensional finite element analysis has been used to model the setups described, with models developed and solved using the COMSOL Multiphysics® simulation package.

Table 1. Base value for thermal modelling parameters

Parameter		Initial value	Comments
Thermal conductivity (k)	General ground	0.8 W/mK	Nominal value for UK soil in [9]
	Sand	1.4 W/mK	Representative value from [10]
	Gravel	0.8 W/mK	Representative value from [10]
	Asphalt	1.4 W/mK	From [11], at approx 50 degrees
	Potting	0.91 W/mK	From [3]
	Ferrite	4 W/mK	From [3]
Ground surface emmisivity		0.97	As per [12]. Also used for wireless pad emissivity (assuming a similar surface finish).
Ground convection		Empirical correlation	Natural and forced convection boundary conditions (COMSOL)
Wind speed		1 m/s	'Light air' [13]
Ambient air temperature		20 °C	Within appropriate range for UK. Initial conditions - all at ambient.

B. Thermal Analysis of Initial Configuration

For 750 W of total power losses within the GA, the temperature distribution for a steady-state model with the base values described in in Table 1 is shown in Fig. 3. For clarity, the power losses here are apportioned to 300 W in the power electronics and 450 W in the wireless pad in accordance to the ratio previously described.

For this level of steady-state heat dissipation and under the aforementioned conditions, the heatsink rises to approximately 65 °C (45 °C above ambient). Such levels of heatsink temperature are generally compatible with modern power electronics. It should be noted that the junction temperatures within the power-electronic components will be higher than the heatsink temperature. Losses in the resonant circuit have also been included within the power electronics loss budget, and under these conditions the long-term performance of capacitors in the resonant circuit for example may need additional design consideration, whereas inductors are likely to be okay. The detailed modelling of individual power electronic and resonant circuit components is outside the scope of this paper, however this paper will examine how the general power-electronics heatsink temperature varies according to thermal design options and environmental conditions.

The maximum temperature rise within the wireless pad under these conditions is approximately 10 °C less than that of the power electronics heatsink, and is compatible with common pad construction materials. The corresponding maximum temperature of the pad surface is around 45 °C (25 °C above ambient), such a level is within typical road temperature variations [6] but higher levels would need to be considered along with requirements for public safety and potential softening of the surrounding road surface. Detailed thermal modelling of the wireless pad is outside the scope of this paper, however a general wireless pad is modelled here and this paper will examine how the surface temperature of that pad varies according to thermal design options and environmental conditions.

(a)

(b)

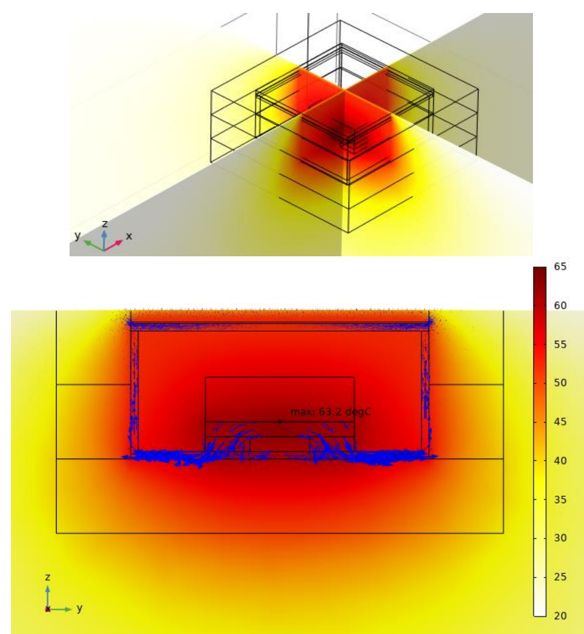

Fig. 3. Temperature distribution (in degrees C) at 750 W total GA losses (a) 3D slice and (b) 2D slice. Blue arrows show the direction of heat flux

As well as temperatures, we can also examine the distribution of heat flux within the model. Evaluation at the ground surface indicates that approximately 50 % of the total heat flux is through the pad surface, and the remaining 50 % through the ground, split roughly equally between the surrounding backfill surface (excavation) and the undisturbed ground surface (outer soil). This distribution indicates the role that the ground has in this model.

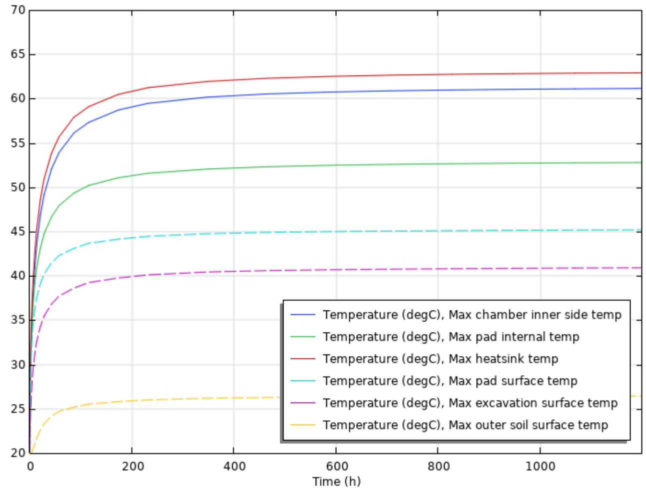

Fig. 4. Temperature vs time at 750 W total GA losses

The results in Fig. 3 are for steady-state conditions. Fig. 4 shows the transient behavior for the same model and indicates that a significant time-constant is involved (circa 50 hours). A long thermal time-constant is beneficial as it allows advantage to be taken of duty-cycle operation i.e. if a charger was only in use for 12 hours in every 24 hour period, the long-term average temperature rise would stabilize at around half of that expected for continuous operation. The type of duty cycle will depend on the application – a typical domestic charger might be in use at a low power overnight and have a fairly smooth heating / cooling profile, whereas for a public rapid charger would likely have many usage sessions during the day with a ratcheting temperature profile then cooling off at night.

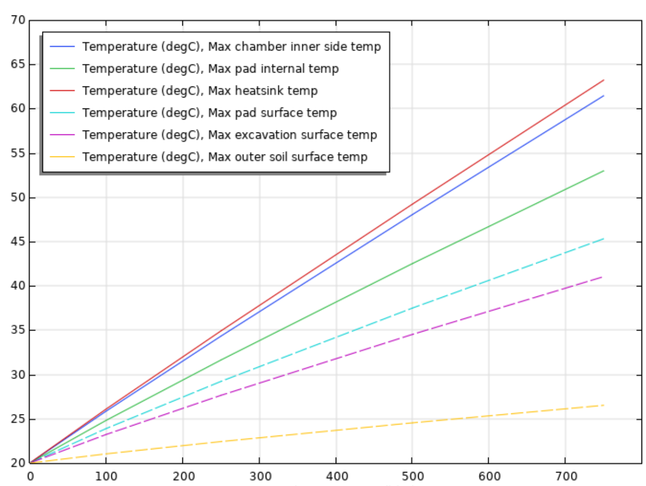

Fig. 5. Temperature vs total GA power loss

The previous figures have shown temperatures at a loss level of 750 W in the GA. To investigate the thermal performance of systems with different GA-side losses, a graph of steady-state chamber side temperature against heat generation within the GA is shown in Fig. 5. Within the range examined, temperature rise (from the 20 ºC ambient temperature) is approximately linear with power loss. Using the same ratio of power losses previously outlined, a 7 kW system at 90 % efficiency would correspond to a total GA power loss of ~525 W and similarly for a 3 kW system the level would be ~225 W. A 10 kW system operating at 93 % efficiency would also correspond to a ~525 W GA power loss level.

The modelling so far highlights the role that overall system efficiency and expected operational duty-cycle has on the temperature levels and thermal management of an in-ground wireless charging installation.

C. *Effect of Environmental Conditions*

The moisture content within the ground has a significant effect on the ground's thermal conductivity. The values chosen in Table 1 are approximately in the middle of the expected ranges for the ground materials indicated. To quantify the effect of changes in ground thermal properties on the model, the thermal conductivity (k) for asphalt, gravel, sand and surrounding soil indicated in Table 1 are swept from half their stated value (generally dry conditions) to double their stated value (very wet conditions). The resulting temperatures are shown in Fig. 6.

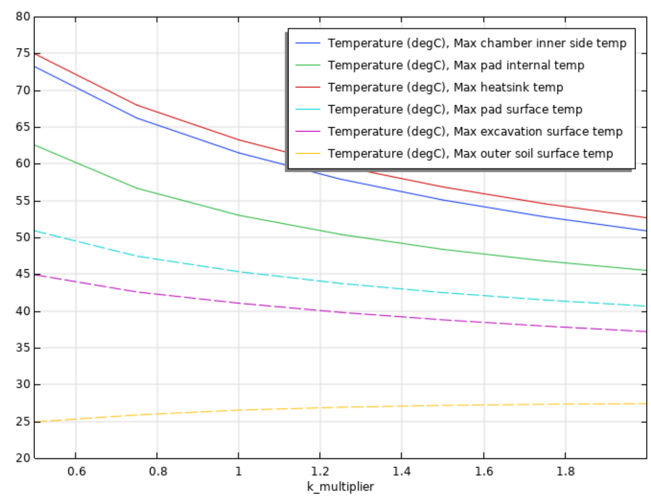

Fig. 6. Steady-state temperatures vs ground material thermal conductivity variation at 750 W total GA losses

Compared to the initial model condition (k_multiplier = 1), adjusting thermal conductivities in the way described leads to a ±20-30 % change in component temperature rise. This is noteworthy from the perspective of thermal management for in-ground installations and allowance should be made for this in the thermal design.

Due to the porous nature of the ground materials, convection is also a potential mechanism of heat transfer within the ground – this is not explicitly modelled here and its inclusion would increase the heat transfer capacity of the modelled ground materials. The variation of temperature with thermal conductivity of the surrounding ground also suggests that one technique which could be used to enhance the thermal performance of an in-road system (to a certain degree, if required) could be to specifically engineer the backfill materials to achieve higher heat transfer capability whilst maintaining the required specifications for strength, drainage etc. Such research is not uncommon in the field of civil engineering and the UK HAUC standards give potential scope to use alternative backfill materials ([5] Appendix 9).

Besides moisture content, another environmental factor that can have an influence on temperature rise is wind speed, with windier conditions enhancing the forced convection heat transfer mechanism at the ground surface. The initial model used a value appropriate to ‘light air’ (Table 1). In Fig. 7 the effect of wind speed is examined for a range of different wind speeds ranging from ‘calm’ to ‘strong breeze’ [13].

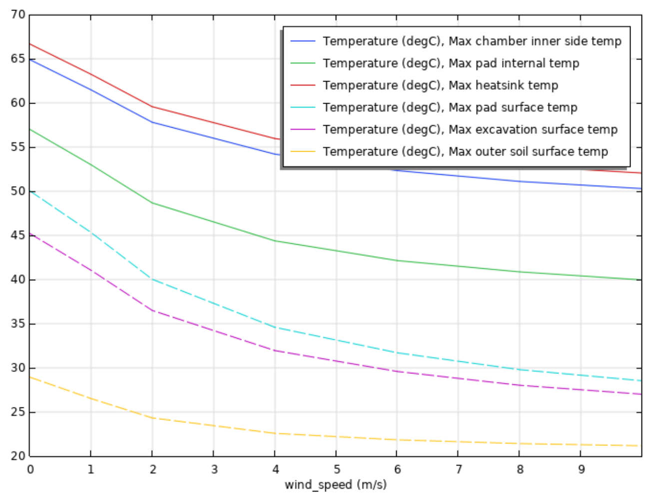

Fig. 7. Temperature vs wind speed at 750 W heat generation

Compared to the initial model configuration (1 m/s wind speed) a 10-20 % increase in temperature rise is noticed under completely calm air conditions and a 25-40 % decrease in strong breeze conditions. In outdoor conditions, some air movement can be expected and it is useful to note its effect on the thermal characteristics of the in-road system. Given the large thermal time constants of the system noted in Fig. 4, it is anticipated that an averaged wind speed for a chosen deployment site would be suitable for thermal design considerations. Alternatively, if higher reliability is required, the worst-case thermal scenario of calm air conditions can be used for design purposes.

There are a number of environmental variables such as the effect of solar insolation and fluctuations in ambient air temperature which have not been included in the model at this stage. These are likely to introduce cyclical temperature variations with time and a topic to be considered in future work.

D. *Effect of Chamber Wall Material and Power Electronics Mounting Location*

A design choice made in the initial model here was to use an aluminium chamber, with the thought that this will help spread the heat from the power electronics box to a large surface area of surrounding soil. The power electronics box was also mounted to the bottom of the chamber, which is only one of the possible mounting locations. This section examines the use of another common material for underground installations, namely GRP (k = 0.49), instead of aluminium as the chamber wall material. Additionally, options for power electronics mounting location – on the bottom of the chamber, on the side of the chamber, and directly behind the wireless pad itself – have been explored. The temperatures of key locations on the model are tabulated in Table 2 for each configuration.

It can be seen that in all cases, the use of GRP as the chamber wall material increases the temperature of the power electronics heatsink highlighting the role the aluminium chamber side plays in distributing the heat to the surrounding ground. The most significant increases by far are for when the power electronics is mounted on the bottom and side of the chamber. In the case of the power electronics box mounted directly onto the back of the wireless pad a much smaller increase is noted, however it is not zero indicating that the chamber walls also have a role to play in transferring heat from the wireless pad to the surrounding ground.

Table 2. Key temperatures for different chamber materials and power electronics mounting locations

	Power electronics box location:	**Bottom of chamber**		**Side of chamber**		**Top of chamber**	
	Chamber wall material:	*Alu.*	*GRP*	*Alu.*	*GRP*	*Alu.*	*GRP*
degC	Max heatsink	63	326	63	297	62	75
	Max pad internal	53	50	58	58	61	73
	Max pad surface	45	44	48	48	50	58

Considering just the case of an aluminium chamber wall, mounting the power electronics to the side or top of the chamber gives very little change in the power electronics heatsink temperature compared to the initial configuration, but it does lead to a temperature increase in the wireless pad by up to 15 %. Depending on the pad materials and the pad surface temperature requirements at the installation site, this may not be an issue leaving the designer free to adjust the mounting arrangement to suit other factors.

E. *Using Internal Air Flow to Transfer Heat from the Power Electronics*

The modelling thus far has used conduction through aluminium legs to transfer heat from the power electronics heatsink to the chamber walls. However, it may not always be practical to achieve direct thermal contact between the chamber walls and the power electronics heatsinks particularly when considering mechanical vibration, shock etc. that the chamber walls may be exposed to. In reality, the heat flow within the chamber is by a combination of conduction, convection and radiation. This section examines the use of force air flow as the dominant heat-transfer mechanism, i.e. removing the aluminium legs and modelling an air-cooled heatsink under the power electronics box with fans to circulate air internally within the chamber.

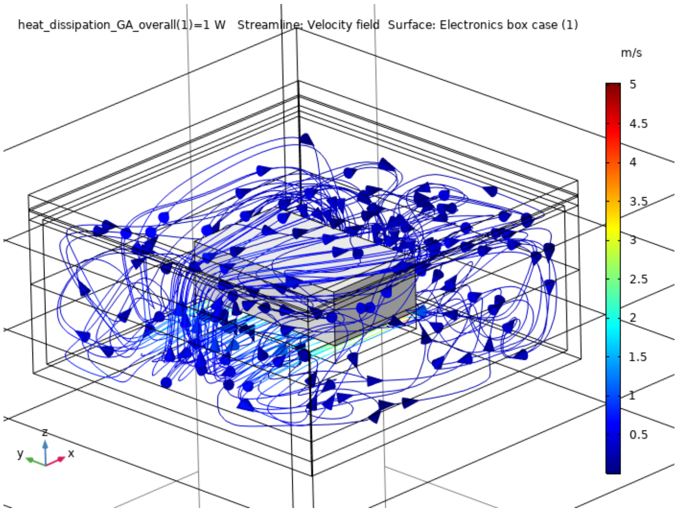

Fig. 8. Velocity streamlines – internal air flow

To investigate this, the thermal model was expanded to a multiphysics model incorporating both air flow and heat transfer modelling within the chamber. The power electronics box was placed in the middle of the enclosure and the parameters for a modest fan (0.75 in H_2O static pressure, 100 cfm free flow rate) applied to generate airflow through the heatsink. The setup, along with streamlines for the resulting airflow within the chamber, is shown in Fig. 8.

Fig. 9 shows the resulting air temperatures within the enclosure for the same range of overall GA power dissipations explored in Fig. 5. For this particular choice of fan, the maximum heatsink temperature is a little higher (approx. 10 ºC) than with the direct conductive connection to the chamber side explored in earlier models. The difference is not large and indicates that the use of air flow to transfer heat between the power electronics and the chamber walls may be acceptable from a thermal design perspective as an alternative to direct conduction.

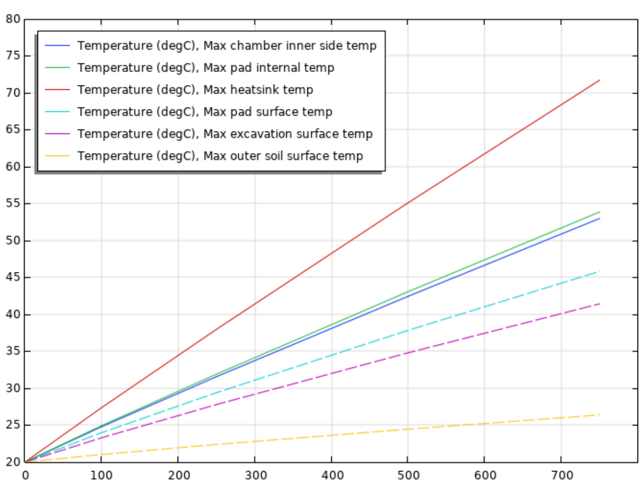

Fig. 9. Temperature vs total GA power loss – with internal air flow

The inclusion of a fan however may not be desirable from a reliability and maintenance perspective. Potential alternative ideas that do not require a completely rigid connection between the heatsink and the chamber side include flexible metal strips or perhaps a liquid circulation loop. It is anticipated that with suitable design, performance comparable to a direct thermal connection to the chamber side walls could be achieved.

IV. Conclusion

This paper has examined and compared a number of different thermal design options and considered the relative merits of each from a quantitative and qualitative perspective. This modelling study suggests that with a thermal design that considers in a unified manner the pad, power electronics and ground enclosure, it is possible to achieve passive thermal management for in-road wireless charging installations exhibiting similar losses to those considered here.

This study indicates that the contribution of the ground to heat transfer can be significant, the system has a large thermal time constant compared to typical durations of a single vehicle charge, a chamber wall material with high thermal conductivity is beneficial, and that there is some design flexibility in the mounting position of the power electronics and mechanism of heat transfer to the chamber wall. Some variation depending on ground moisture content, and other environmental operating conditions is expected.

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