Traction System Cooling Options for Electric Vehicles

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Abstract

Electrification of vehicles intensify their cooling demands due to requirements of maintaining electronics/electrical system below their maximum temperature threshold. In this paper, passive cooling approaches based on heat pipes has been considered for the thermal management of electric vehicle (EV) traction system including battery, inverter and motor. For battery, heat pipe base plate is used to provide high heat removal (180 W per module) and better thermal uniformity (< 5 C) to battery module in a pack while downsizing liquid cold plate system. In the case of Inverter, two phase cooling system based on heat pipes were designed to handle hot spots arising from high flux (~100 W/cm^2) – for liquid cooling, and provide location independence and dedicated cooling approach - for air cooling. For EV motor, heat pipe based system are explored for stator and rotor cooling. The paper also provide glimpse of development on high performance microchannel based cold plate technologies based on parallel fins and multi-layer 3D stacked structures. Specifically, this work extends the concept of hybridization of two-phase technology based on heat pipes with single-phase technology, predominately based on liquid cooling, to extend performance, functionalities and operational regime of cooling solutions for components of EV drive train. In summary, heat pipes will help to improve overall reliability, performance and safety of air and liquid cooling systems in electric vehicles.

Keywords: Li-ion battery, Inverter, motor, Electric vehicle, Heat pipe, Two-phase cooling, High performance cold plate.

1. Introduction

Electric vehicles have electric propulsion system that includes battery system, traction inverter and electric motor as the main components for automotive traction. These power systems are supported by auxiliary components for power transmission (cabling), power conversion (Invertor, DC/DC convertor) and battery charging (onboard/induction charger, charging port). Figure 1 presents that simplified form of vehicle electric power train with charging system from inlet port to battery, and discharging system (or traction system) from battery to motor [1, 2]. In Figure 2, heat output from different components of traction system is presented, along with automotive electronics (e.g. display, headlamp, ECU) for comparison purpose. It can be seen that power systems covers wide range of load-distance spectrum with general trend towards high power and longer heat transfer distances. In other words, thermal solution for electric vehicles will need to be develop to handle high flux and transfer high power over significant distances while satisfying robust structural quality. Such requirements are unique for two-phase and single-phase systems originally developed for consumer and high performance stationary electronics. Thus, necessitate focus on development of high performance, modular and dedicated thermal systems for electric vehicles.

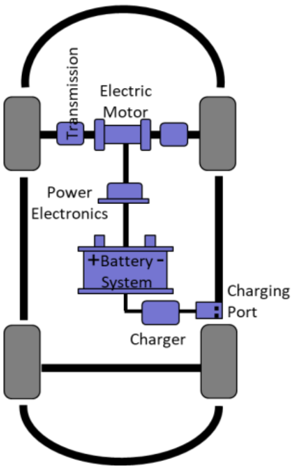


Figure 1. Electrified propulsion system in electric vehicle showing battery system and motor along with control electronics

Electric vehicle, in contrast to engine vehicle, have more specific and specialized cooling needs. Specific needs because of high sensitivity of electronics and electrical systems to temperature. Engine vehicle generally uses materials, which have high tolerance to wider temperature ranges. Specialized needs because of exclusive requirements and design customization needed per system functionalities and specifications. For example, EVs typically require cooling solutions for high voltage systems with isolation needs to prevent short-circuiting. New generation optical systems in headlamp and display have low temperature requirements to maintain good optical performance from such devices. Although, EVs are predominately built out of electronic/electric systems that are made of materials which are thermally sensitive to temperature for performance and structural integrity. However, there is general trend in automotive, including engine vehicles, towards higher electrification arising from autonomy and computerization of vehicular functions. Therefore, overall cooling requirements in automotive are on the rise.

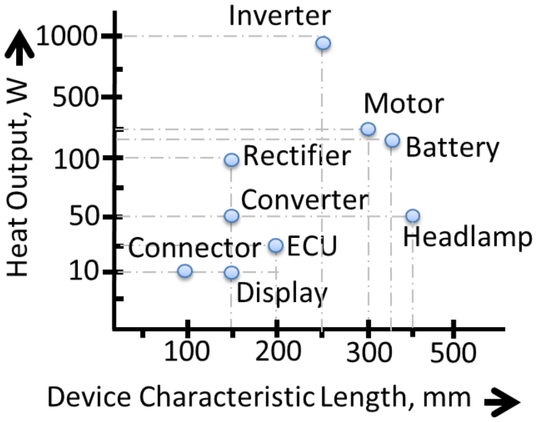


Figure 2. Waste heat output from different electronic/electric system in car

As stated earlier, overall electric propulsion system consists of electric system (like cables, connector, fuse, motor), electronic system (like inverter, converter, OBC) and electrochemical system (like Li-ion batteries). Each of these categories have very specific cooling requirements due to different materials and functions of these systems. Additionally, each system even in similar categories have diverse thermal challenges owing to their electrical architecture (or simply design), location in car (front, back, in-cabin, under-cabin) and cooling method (air-base, liquid-base, conduction to chassis). Cooling requirements of these devices could be dictated by material temperature limits (SiC chip have higher temperature limits than Si chip), criticality of system (autonomous drive system need higher redundancies than infotainment system) and sometime mere system cost (to avoid replacement costs).

For simplicity, in this paper, we have chosen three major systems from electric drive train to provide an overall overview on types of cooling requirements, thermal solutions development at component and overall device level that are needed in area of traction systems.

Most components of electric drive train requires thermal management for performance and longevity. Electrical (e.g. e-motors) and electronic systems (e.g. IGBTs – inverter, converters) can sustain higher operating temperatures (~ 100 to 150°C) than electrochemical systems like battery cells (~ 40 °C) [3]. Lithium-Ion cells, in either prismatic or pouch form, are invariably used for automotive batteries owing to their high energy density and better charging-discharging efficiency. For good calendar life and performance of Li-ion battery, temperatures should be maintained within narrow temperature range ~ 25 to 40 °C. For the battery electric vehicle (BEV), the range can reduce by 18% when driving on hot summer day (+35 °C, 40% RH) and by 36% when driving on cold winter day (~ -10 °C, 90% RH), due to cabin and battery thermal management. Based on aforesaid facts, it can be safely asserted that thermal management of automotive batteries is very critical for vehicle range (economy), performance and lifetime cost.

Traction inverters, also commonly referred as power electronics, provides a controlling and switching link between battery and motor. Development in inverter have provided variable challenges for cooling system to handle high heat fluxes (35-100 W/cm^2), large heat loads (1-2kW) while keeping working temperatures within limits of semiconductor materials used in inverter built.

Motors have main heat source as bearing and electrical coils. Both components can sustain temperature level 100-150 °C range. Motor could be cooled at stator or rotor area depending on motor type, design and main areas of thermal generation. For rotor cooling, main challenges comes from the fact that heat source is in rotational motion so cooling system will be required to give thermal and structural performance while in high RPM motion.

Figure 3 present thermal roadmap for electric vehicles that help to identify applicable cooling technology w.r.t heat ranges. In light of above discussion, it is important to understand that existing state of cooling technology in vehicle has been mainly developed to manage engines and other mechanical systems, and therefore could not provide an efficient migration to vehicles with significant electric built (plug in hybrids - PHEVs, battery electric vehicles - BEVs). Electronic/electric systems in EVs gives out concentrated heat fluxes, which need to be managed by highly developed cooling system (single phase as well as two phase). Per Figure 3, there is an opportunity to improve operational regime for air cooling, two-phase solutions as well as liquid cooling within capability index of respective technology. Particularly, hybridization or optimum mixing of technologies would help to provide cooling design breakthroughs in area of traction drive train.

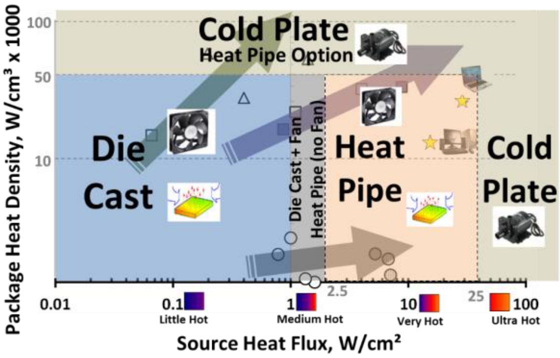


Figure 3. Thermal Roadmap for Automotive

In this paper, cooling challenges for components of EV drive train has been outlined for relevance of current work. Technological improvements in area of two phase and single phase have been outlined, followed by enhanced cooling systems built and characterization as outcomes of present research undertaking.

2. Cooling Device Requirements

As discussed in previous section, different components in electric power train have different permissible temperatures (owing to material, reliability needs), structural (owing to component location, built), electrical (owing to voltage class – low, high) and operational (owing to functional modes – sudden surge, steady, transient) requirements.

The cooling device is designed to achieve required thermal resistance, – R_t, as determined by its source permissible temperature (T_h) and output heat load (Q^*) for given sink temperature (generally ambient air – T_c). it can be represented mathematical as:

$$R_t = \frac{(T_h - T_c)}{Q^*} \qquad (1)$$

Other requirements are more component specific and targeted to achieve maximum performance and lifetime for the device while operating reliably and safely. Cooling device should be able to maintain temperature uniformity within ±5°C over active heat source to reduce thermal stress on semiconductor surface or Li-ion cell. For high voltage devices, cooling device need to maintain isolation gap of 1-2 kV/mm (depending on voltage and proximity of other power sources). In traction invertors, cooling device need to possess 2 to 3 times higher cooling capacity or thermal mass to overcome and absorb sudden power surges of waste heat during vehicle acceleration/deceleration. Similarly, charging line components and battery system need to have adequate cooling means to keep temperature within allowable ranges during normal/fast-charging cycles. In addition to these, thermal solution are require to satisfy lifetime requirements regarding freeze sustainability, cyclic temperature operation, high temperature endurances and alike. Geometrical tolerances and structure of device should keep intact during designed lifetime.

3. Technology Enhancements

In this section, cooling technologies of interest in thermal management of traction system of EVs has been identified with key developments that has been in effect to make these technologies more application in terms of performance, reliability and cost. Figure 4 present length versus capacity for different cooling technologies with solid conduction at lower bands, two phase solution covering most of low to medium band and liquid phase towards long distances and high heat load bands.

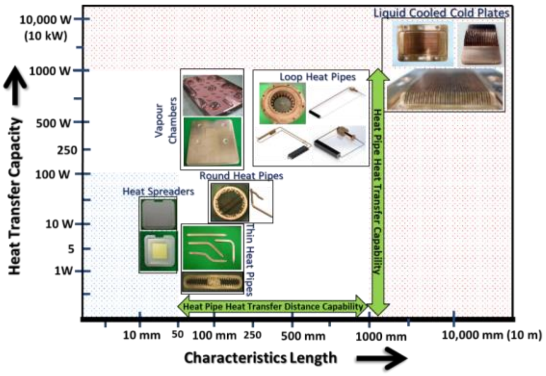


Figure 4. Heat transfer performance of different cooling technologies

3.1 Heat Pipes

In EV thermal management, heat pipes have significant scope to apply as high conductive heat transfer devices in air as well as liquid cooled system. Heat pipes could complement cooling solution in following different ways:

① Enhance temperature uniformity or reduce hot spots

② Reduce liquid leakage hazard in proximity of high voltage area (due to limited liquid in heat pipe. No drip leak)

③ Improve thermal response of cooling solution for sudden power surges

④ Increase thermal capacity of overall cooling system

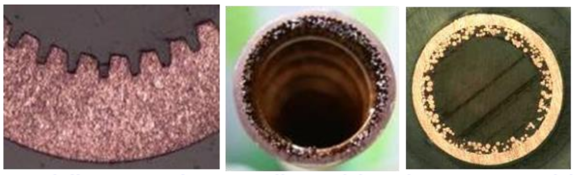

Axially Grooved Fibre Wick Sinter Power Wick

Figure 5. Types of heat pipe wick structure

Typically, heat pipe constitutes of axial, fibre or sinter power wick as shown in Figure 5. In order to enhance effective thermal conductivity of heat pipe and overall heat load, wick design could be enhanced in different ways. Fibre wick is beneficial to achieve smaller thicknesses for heat pipe while keeping high heat capacity whereas power wick helps to achieve high evaporative/condensation heat transfer coefficients along with high capillary pressure for heat transfer against gravity. Figure 6 present heat transfer capacity of diameter 9.4 mm heat pipe with 0.5 and 1 mm thick copper powder wick. As evident, thermal capacity of heat pipe could be almost double by choosing appropriate size and thickness of wick.

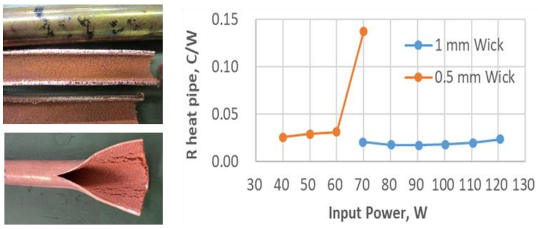


Figure 6. Thermal performance of powder wick with different thicknesses

In Figure 7, heat transport capacity and thermal resistance of 570 mm long heat pipe have shown to improve by using combination of fibre and powder wick. Maximum heat load of 50 W was achieve while thermal resistance was improved from 0.5 to 0.09 °C/W. Such enhancements are possible due to best mix of permeability (possible from linear flow passages in fibre wick), and capillary pressure/phase heat transfer coefficients (possible from fine pore size of powder wick). In this case, relative placement and geometrical design of two wick types is important to achieve best mix of thermal capacity and thermal resistance (or thermal conductivity) of heat pipe.

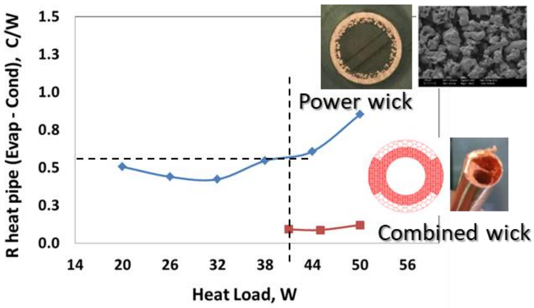


Figure 7. Power versus combined wick thermal performance

Further approaches based on surface texturing of wick by micro powder deposition on fibre/powder to improve wettability, mixing high conductive carbon fibre with copper fibre to enhance wick thermal conductivity, gradation of wick along heat pipe length to achieve best mix of flow properties, and variable thickness of wick around heat pipe cross section to achieve best thermal hydraulic performance from wick has been attempted to improve workability of heat pipe for electric vehicles cooling.

Structural enhancements of heat pipe in terms of improvement in container strength using different alloy of copper, 3D bending/shaping by altering wick alignment, corrosion protection by painting/Ni-plating, and high voltage isolation by polyimide/ceramic coating has been attempted, to apply this technology successfully for automotive. Figure 7 presents heat pipe coated with polyimide to achieve >5V/mm voltage isolation for traction inverter application.

Figure 7. Heat pipe with electrical isolation

3.2 Cold Plates

Liquid cooling is one of main mode of heat removal from components of traction system owing to high heat load per component, and necessity to cool multiple component by single cooling infrastructure. Battery systems are generally very low flux (< 1 W/cm^2) and thus can be cooled by low performance macro channel cooling plates. For power electronics, including traction inverter, DC-DC converter and on-board charger, highly developed cold plates based on microchannel technology are needed to achieve cooling performance expected by devices. In Figure 8, two different version of cold plates based on; 1) Parallel micro channel technology and 2) Multi-stacked layer technology are presented.

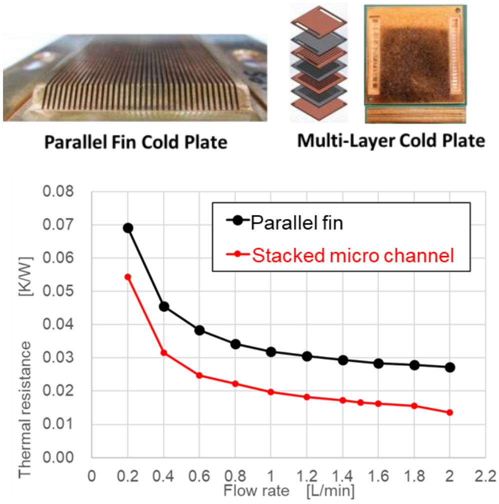


Figure 8. Cold plates based on microchannel technology: Design and expected thermal performance

Parallel channel based design provide simpler and cheaper option whereas multi-layer design offers more performance (~ 40% higher) achieved through 3D stacked structure (5 to 7 stacked layers). Stacked layer structure provide lower pressure drop (due to shorter flow path), lower thermal resistance (due to 3D heat and fluid interaction) and smaller form factors (due to possibility to fabricate such structures through micro etching techniques) but at higher costs. In Figure 8, thermal performance of two types of cold plate structure is presented with respect to flow rate.

Based on aforesaid discussion on applicable cooling technologies, in next section, cooling architectures for thermal management of different components based on two phase and single phase (predominately liquid cooled) hybridized system has been presented.

4. Traction Systems Cooling

In this section, cooling system based on combination of two phase and single phase for three main components of traction system namely battery, inverter and motor are presented, with an aim to provide current state of applicability and improvements needed in order to make such system more viable for electric drive train cooling in EVs.

4.1 Battery Cooling

Most of cabin base in EVs are occupied by battery modules arranged in packs, and customarily cooled by low-end cold plates positioned under the modules. Such cooling system poses safety issues from liquid leakage in high voltage areas, presents temperature gradient within/amongst modules, have heavy weight due to extend of liquid coolant and cold plate volume, and have high system complexity (cold plate integration and connectivity).

In this case, two-phase systems based on heat pipes can extend significant advantages to improve temperature uniformity, reliability and safety [4, 5]. Figure 9 present cooling approach for battery pack with heat collection using heat pipe carrier plates and heat transfer to radiator area using significant downsized cold plate.

Each heat pipe carrier plate was more than 600 mm long with condenser area ~ 50 mm, and was required to transfer 240 W heat load from 1.5 share of battery modules per heat pipe carrier plate. Heat pipe plate provide temperature uniformity within ± 5 C and significant temperature reduction (~ 40 °C) compared to metal Aluminum plate design. Pack level cooling approach as presented in Figure 9 is readily easy to apply and integrate in the vehicle without any major mechanical changes. However, benefits from such methodology approaches limits as extent of heat load increases from next generation high voltage batteries, and even low voltage batteries during fast charging sequences.

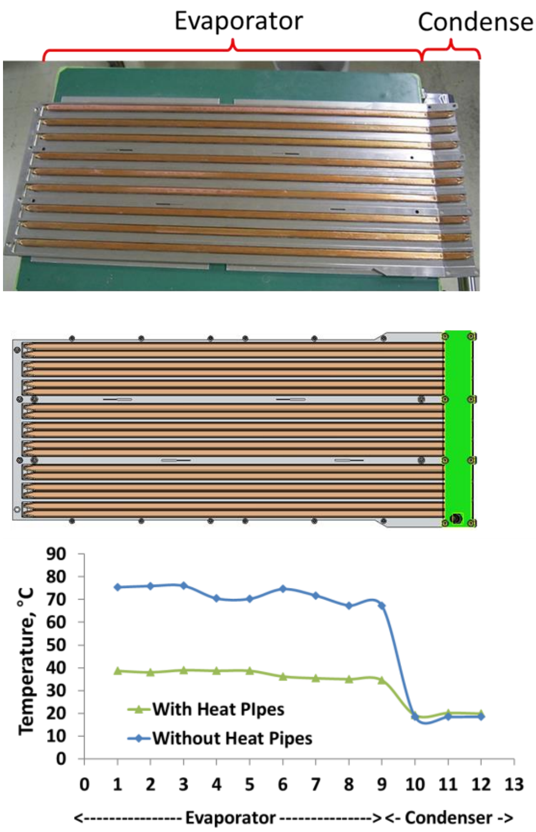
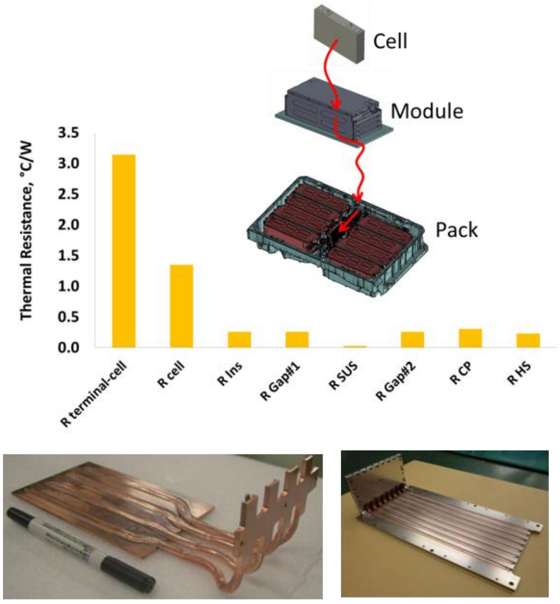


Figure 9. Heat pipe carrier plate for cooling battery pack

Figure 10 shows the breakdown thermal resistance from cell terminal to battery radiator that clearly shows that bulk of thermal flow obstruction lies close to generation areas inside cell. This means targeting efficient heat flow elements (like heat pipes) closer to cell generation areas, although difficult to implement, would provide best cooling benefits in the form of temperature drops. Two such approaches based on module and cell level cooling are shown in Figure 10 (bottom). Cell level cooling approaches has been investigated in details by integrating heat pipes externally or internally in Li-ion cells [6, 7].

It should be noted that mix of two phase and single-phase system, as outlined above, would provide most performance and cost optimum approach for battery cooling [4]. Fully two-phase system are high performance but integration and cost intensive. Similarly, fully single-phase system are bulky, complex and low performance (particularly thermal non-uniformity close to battery cells). The innovative aspect of using heat pipes in battery cooling is hybridization of two-phase and single-phase systems to improve performance and simplify design.



Cell Level

Module Level

Figure 10. Battery system breakdown thermal resistance (top), Cell and module level cooling approaches with heat pipes (bottom)

4.2 Inverter Cooling

Power or traction inverters are located between battery and motor, and perform power controlling and switching functions. Typical EV inverter consists of multiple chips with control electronics, and heat load ranging from 0.5-2 kW. Hot spots and thermal uniformity are typical cooling challenges for inverters [8]. Traction inverter in EVs are generally liquid cooled, except in very specific circumstances when inverter is located far from liquid cooling loop these could be air cooled. In either case, air or liquid cooling, limited thermal conductivity of metal spreader between inverter chips and liquid flow possess limit on maximum heat transfer, system response time and hot spot issues.

Figure 11 presents dedicated air-cooled system for traction inverter based on heat pipe heat sink [9, 10]. The system was designed to handle more than 35 W/cm^2 flux from 3x chips, with total heat load exceeding 1kW in continuous operation, and 2kW during power surges imposed at acceleration/deceleration cycles. Advantages from such systems include design simplicity, allow independent placement of inverter remote from liquid cooling loop, better thermal uniformity than single phase cooling and operational reliability.

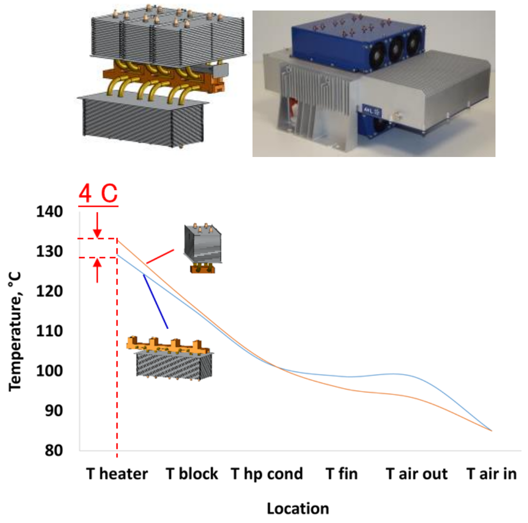


Figure 11. Air-cooled traction inverter for EV with heat pipe spreading and transport: Design and performance characteristics [10]

Temperature uniformity of inverter chips with heat pipe based spreading is represented to be within 4 °C, in Figure 11, which is difficult to achieve, by purely metal spreaders. Nonetheless, liquid cooling of traction inverter provide more compact and high performance system, however single phase does poses limitation to handle hot spots on chips, which has dual heated faces in many cases.

Local spreading enhancement with heat pipes from die to coolant flow face could provide dual benefits of improving cooling response time as well as cooling performance as shown in Figure 12. In this case, heat pipes tend to diffuse hot spots and increase dissipation area from heat sink to coolant by increasing fin efficiency.

Further, passive two-phase system based on heat pipe and vapour chamber are under development to handle fluxes higher than 100 W/cm^2 from next generation of SiC (Silicon Carbide) inverters. In this case, heat pipes with non-homogenous structured wick structure, as discussed in Section 3.1, have been developed to handle high heat load and thermal fluxes. Vapour chamber have higher potential to reduce temperature of dense hot spots as compare to heat pipes, however the form factor and cost of these devices will need to be reduce to make them viable for application in automotive. Additionally, single phase liquid cold plate technologies based on impingement and 3D heat transfer concept, as discussed in Section 3.2, have been developed to improve heat transfer coefficients on liquid side of cooling solution.

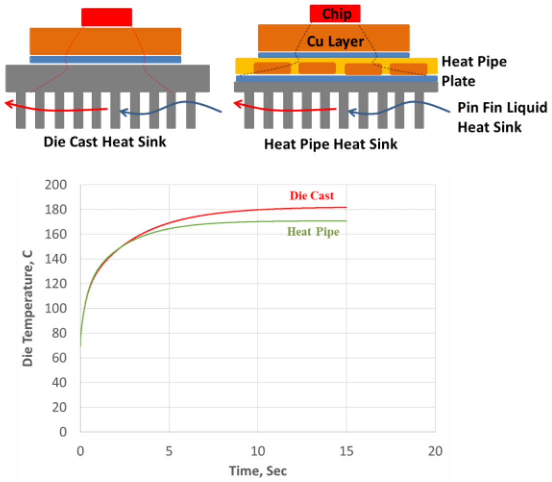


Figure 12. Liquid cooled traction inverter for EV with heat pipe spreading: Design and performance characteristics

4.3 Motor Cooling

Cooling of electric vehicle motor is important for overall performance and longevity of electro-magnetic system and associated control electronics. There are different method for cooling motor including stator cooling and rotor cooling (as shown in Figure 13). Thermal management at stator provide limited cooling due to presence of high thermal resistance path from heat source (coil) to heat sink (circulating air or water). In this case, direct cooling of rotor provide superior cooling option however there are different implementation and operation challenges due to high speed rotation of rotor during operation.


Heat Pipe for Motor Coil Cooling

Heat Pipe Cooled Rotor

Figure 13. Heat pipe options for electric motor cooling

Components in motor that need thermal management include bearing and coils. In this case, heat sources need to have thermal coupling with cooling solution while maintaining electrical isolation to avoid internal short-circuiting and external current leaks via cooling elements. Reliable integration of heat pipe(s) to coil and motor parts to avoid bending of parts during rotation, balancing of parts in rotation (to avoid any residual unbalance forces on rotating parts) and sealing of coolant fluid around rotating parts need to be given due consideration in the design and implementation of two phase cooling system for motors. Still, rotational heat pipes have undergone limited investigation and applications due to their complex thermal fluids behavior and mechanical interactions. Further work on these devices will need to be done to apply them in cooling high-speed motors in EVs.

5. Conclusions

The paper have provided mix of two-phase and single phase cooling approaches for components of electric drive train of vehicle with cooling performance in range of 0.5 to 2 kW, ~ 35-100 W/cm^2 heat fluxes. In summary, heat pipe based passive system will provide system with high runtime reliability, better thermal uniformity and more safety, for battery, inverter and motor cooling in electric vehicles.

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