Fundamentals of a Floating Loop Concept Based on R134a Refrigerant Cooling of High Heat Flux Electronics

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Abstract*

The Oak Ridge National Laboratory (ORNL) Power Electronics and Electric Machinery Research Center (PEEMRC) has been developing technologies to address the thermal concerns associated with hybrid electric vehicles (HEVs). This work is part of the ongoing FreedomCAR and Vehicle Technologies program (FCVT), performed for the Department of Energy (DOE). Removal of the heat generated from electrical losses in traction motors and their associated power electronics is essential for the reliable operation of motors and power electronics. As part of a larger thermal management project, which includes shrinking inverter size and direct cooling of electronics, ORNL has developed U.S. Patent No. 6,772,603 B2, *Methods and Apparatus for Thermal Management of Vehicle Systems and Components* [1], and patent pending *Floating Loop System for Cooling Integrated Motors and Inverters Using Hot Liquid Refrigerant* [2]. The floating-loop system provides a large coefficient of performance (COP) for hybrid-electric drive component cooling. This loop (based on R-134a) shares a vehicle's existing air-conditioning (AC) condenser, which dissipates waste heat to the ambient air. Because the temperature requirements for cooling of power electronics and electric machines are not as low as that required for passenger compartment air, this adjoining loop can operate on the high-pressure side of the existing AC system. This arrangement also allows for the floating loop to run without the need for the compressor and only needs a small pump to move the liquid refrigerant. For the design to be viable, the loop must not adversely affect the existing system. The loop would also provide a high COP, a flat temperature profile, and a low pressure drop.

The floating-loop test prototype has been successfully integrated into a 9 kW automobile passenger AC system. In this configuration, the floating loop has been tested up to 2 kW of heat rejected during operation with and without the automotive AC system running. The floating-loop system has demonstrated a very respectable COP of 40–45, as compared to a typical AC system COP of about 2–4. The estimated required waste-heat load for future HEV cooling applications is 5.5 kW, and the existing system should be easily scalable to this larger load.

Keywords

Direct Cooling, Two-Phase Cooling, R134a, Refrigerant, Thermal Management, High-Heat Flux Electronics, Floating Loop, Hybrid-Electric Drive Cooling

1. Background

Currently, HEVs use several different methods to cool the drive system. An HEV drive contains an electric traction drive motor, power electronics to supply the motor, some gear train components, and a cooling system of some type. Benchmarking work done by ORNL revealed that current cooling schemes by leading auto manufacturers include 50/50 water/ethylene-glycol (WEG) heat sinks, forced and natural air convection, oil circulation, and combinations of some of these. While the above systems are effective as heat exchange systems, liquid based systems operate at a temperature of 65°C [3] for vehicles using a separate dedicated radiator, and about 105°C when operating in conjunction with the engine radiator. At junction temperatures of 125°C, the silicon-based power electronics devices begin to lose reliability and at 150°C the devices begin to break down. Cooling systems with a bulk temperature of around 105°C push the electronics to their maximum operating limits.

Furthermore, the windings in the electric traction motor(s) must be kept within the temperature rating of the stator-insulation material. Without appropriate cooling, the motor performance will decrease. With improved cooling, the motor can run at a higher efficiency due to decreased resistive` losses in the windings. Currently, there are three paths that are used in vehicles to remove heat from the various systems to the ambient air. These include the internal combustion engine

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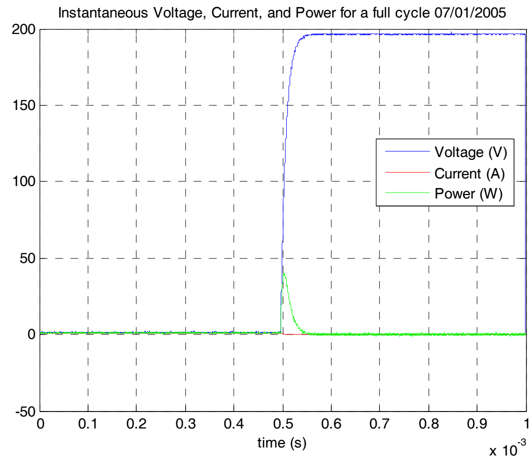
(ICE) cooling system (105°C WEG), transmission oil flowing through a separate cooler (85°C), and the passenger compartment AC refrigerant system (currently R134a refrigerant at about 60–80°C condenser temperature).

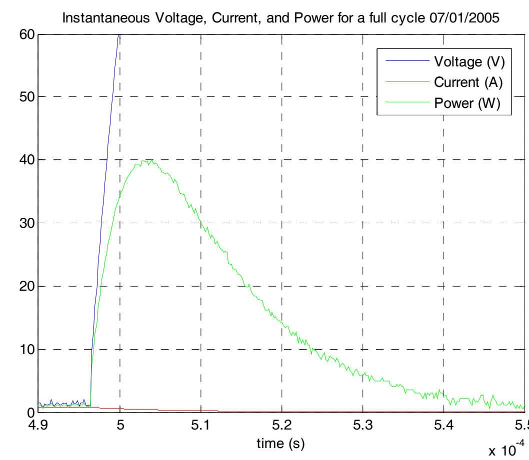
The floating loop is a novel approach to the heat removal problem. It takes advantage of R-134a dielectric properties and temperature ranges, works well in compact heat exchangers, and could be used to cool larger structures like a motor housing. Previous work at ORNL demonstrated the very good dielectric nature of R-134a. Life tests with capacitors, an insulated gate bipolar transistor (IGBT), and a gate-driver printed circuit board (see Figure 1) showed no adverse affects when in direct contact with the refrigerant. The life tests have been conducted over a period of 21 months, with periodic functional tests of the circuitry and visual inspections of the components and wiring occurring about every 3–4 months [4].

Figure 1: Silicon IGBT and gate-drive electronics submerged in R134a refrigerant for 21 months in continuing test.

The electronics were studied during the soak period to evaluate effects of dielectric fluid directly surrounding the electronics. It was theorized that the fluid characteristics may affect the high frequency switching abilities of the circuit due to being surrounded with the new fluid as opposed to air. Experimental tests showed no switching differences between air and R134a refrigerant surrounding the electronics. It was also desired to determine if any long term effects would be found from this particular refrigerant soaking the components and wiring for long periods of time. One parameter studied is shown in Figures 2 and 3. It was determined that the switching characteristics of the IGBT under study were unaffected after a total of 21 months (the testing continues). Figures 2(a) and 3(a) show the full switching cycle at turn-off, and Figures 2(b) and 3(b) show a zoom-up of the power trace around the off-event to detect changes in switching power losses. The switching events in these two cases were found to be essentially identical, indicating no degradation in components or circuitry. The ripple on the power trace in Figure 3(b) is believed to be due to filtering effects and sampling rates between two different analyzers.



(a)



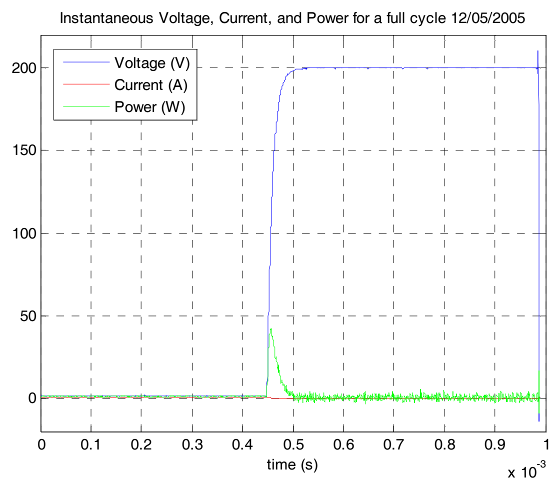
(b)

Figure 2: Switching characteristics of IGBT for an off-switching event (R134a extended soak after ~13 months).

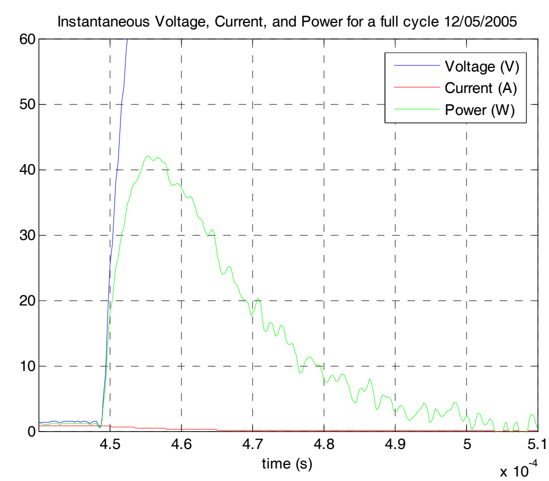
With electronic components operating at higher efficiencies, fewer and smaller devices can be used that can result in lower part count and reduced silicon material cost for the hybrid-electric drive. Ultimately, the development of the floating loop is the first step by ORNL in a plan to significantly shrink the size of the traction drive and its associated high-heat flux electronics while maintaining net power output [5].

2. Proof of Concept

The basic concept of the floating loop is based on a low pressure drop refrigerant circuit that is connected in parallel with the condenser of a conventional automotive AC system. The condenser is the highest pressure zone in the AC system, so the floating-loop circuit and components exist in this higher pressure zone. Figure 4 shows the operating zone in a R134a pressure-enthalpy diagram where the parallelogram in Curve 2 denotes the typical auto AC operating region, and Curve 1 superimposed on the top of this region is the operating zone of the floating loop. The Curve 3 trapezoid shows how the cycle operates when only the AC system is operating, with no floating-loop loads.



(a)



(b)

Figure 3: Switching characteristics of IGBT for an off-switching event (R134a extended soak after ~18 months).

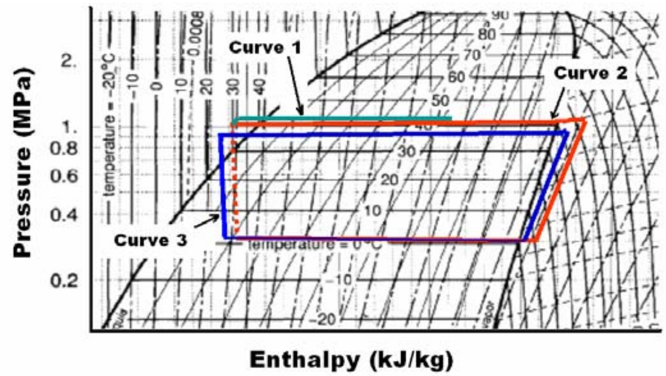


Figure 4: Pressure-enthalpy diagram showing operating regime of the floating loop.

The floating-loop subsystem itself consists of a heat load/cooling zone and a small pump to motivate fluid in the proper direction. It is a two-phase cooling scenario, but with an extremely low overall pressure drop (about 1 bar). The liquid produced in the system condenser is fed through the loop pump into the load where the liquid absorbs the load energy and converts to vapor. The vapor moves to the system condenser to restart the cycle. This is all happening in parallel with the existing auto AC system that is operating simultaneously.

To demonstrate this refrigerant cooling concept for power electronics, three main test cases were devised:

a. Load test on Loop by itself
b. AC system test with Loop installed but idle
c. AC system and Loop functioning simultaneously

Case (a): Load Test on Loop by Itself

The first goal was to show that a significant heat load could be removed with no compressor. This system only requires a very small pump to motivate fluid flow in the correct direction, and overcome increased backpressure when the AC system is operating.

A typical refrigeration system creates a relatively cold low-temperature zone compared to ambient temperatures, and this requires a high pressure difference (and thus a compressor and expansion device) in the refrigerant system. Unlike home interiors or automobile passenger compartments (~20°C), the electronics and motor in a hybrid-electric drive can operate at a relatively high temperature (60–80°C), and this difference enables the floating-loop cooling concept. This system can then operate with a very small pressure difference, and therefore does not incur any energy-intensive high pressure losses. The refrigerant would be moved in the system with a liquid pump or vapor blower, which requires minimal input power. Vapor is generated in the heat load zone of the floating-loop system, which then moves to the condenser where heat is rejected to the ambient environment.

This test case would prove that a low-pressure-drop, high temperature, two-phase coolant loop would remove sufficient heat to be a viable hybrid-electric drive cooling concept.

This portion of the testing was done with a bench-top setup consisting of a variable speed pump, a heat source, and a condenser (shown in Figure 5). This cooling loop removed more than 2.1 kW of heat load with minimal input power, with the system temperature running around 80–90°C. A pump was used with input power of 48 W. This cooling loop configuration resulted in a COP of about 44. The COP in this example is calculated as follows:

COP = Heat rejected / input loop power required

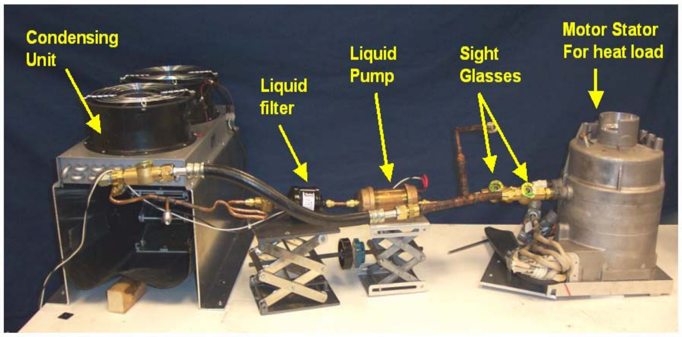


Figure 5: Floating-loop bench top apparatus with pump.

<u>Case (b): AC System Test with Loop Installed but Idle</u>

The second test case would involve integrating a similar loop, such as in Case (a), into an automotive AC system where the new loop and AC system would share the condenser in a parallel fashion. The objective of Case (b) was to prove that the loop could share the condenser without adversely affecting the inventory behavior or performance of the automotive AC.

A "full hybrid" vehicle utilizes high power electric traction drive, comparable in capacity to the internal combustion engine. These two power sources can work together or individually as needed by the system demands. In a full hybrid setup, the loop is required to operate continuously to cool the power electronics that will always be operating. In this full hybrid configuration, the power electronics would be required to power up first in order to drive the small loop pump and traction drive, then the AC compressor if needed, and other electrical accessories as required. In other words, the floating-loop cooling system would be running under any of the full hybrid operating scenarios.

In an assist-only hybrid configuration the power electronics and traction motor may not be required to operate under many conditions. This configuration exists only where the ICE runs all the time and the electric drive is intermittent (i.e. assist mode). Testing for Case (b) was set up for the assist mode of operation, to evaluate the operation of the AC system only with the floating-loop subsystem connected but idle.

To prepare for this test case, an automotive AC system was required to allow integration of the basic floating-loop sub-system. In order to provide a testing platform in the laboratory, parts from a full-size sedan AC system were procured and installed in a cabinet, providing a stand-alone AC unit based on the automotive design. The laboratory test platform has a cooling capacity of about 9 kW. Figure 6 shows a photograph of the actual laboratory test cabinet. Figure 7 shows a schematic layout of the original system installed in the cabinet.

Figure 6: Revised floating loop attached to full size sedan AC system in a cabinet.

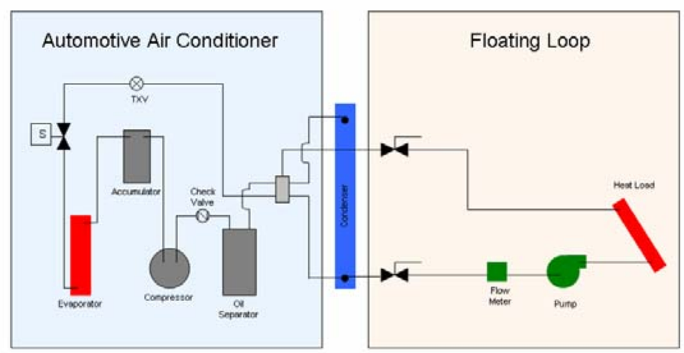


Figure 7: Schematic of original floating-loop configuration adjoined to the cabinet AC system.

The floating-loop inlet line (pump suction) was placed at the lowest elevation possible to ensure the pump inlet would remain flooded with liquid without undue increases in system inventory. A maximum 1 kW test load was initially used to test loop operation, and the loop was capable of maintaining the test load at approximately 30°C. It is believed that the system will handle a larger load, but higher load levels were not necessary for proof of the concept.

After the systems had been operated together for some time, it was desired to see effects on system inventory, i.e. to see if inventory migrated to undesired parts of the new combined system. Next, the loop was isolated from the stock AC system, and was found to still produce the required amount of cooling for the 1 kW load. This test showed that loop operation had no adverse affect on refrigerant inventory behavior or refrigerant migration.

<u>Case (c): AC System and Loop Functioning Simultaneously</u>

The test involved operating the floating loop and AC system simultaneously. This configuration would be indicative of normal operation of the floating loop in a full hybrid configuration, where the floating-loop/hybrid drive cooling system is operating as the primary system, and the AC system runs simultaneously to cool the passenger compartment.

This final test involved operation of both systems simultaneously. The loop cooled the 1 kW test load and maintained it near 40°C. This increase in temperature from the previous 30°C in the loop-only scenario is a result of the increase in condenser heat load (and thus condenser pressure and temperature) when the compressor is running. When the loop runs by itself, the condenser pressure is around 650–720 kPa. When the AC system and loop are running simultaneously, the condenser pressure is near 1 MPa. One key element in obtaining stability in these results was to provide increased air flow across the condenser. Some previous tests exhibited unstable behavior under certain conditions due to lack of proper air flow through the condenser.

For all tests, the condenser inlet air temperature was about 25°C from the ambient laboratory air condition.

3. Design Evaluation

Overall, the floating-loop system met the initial design goals; however, these tests revealed several concerns with the combined loop and AC system dynamics. Oil traps and liquid refrigerant traps had been unintentionally created during the integration of the loop into the automotive AC system, as well as due to installing the automotive system in the laboratory cabinet. Liquid migration and flash boiling in the floating loop portion of the system during compressor cycling was also discovered to be a problem. Load dry-out is considered to be a major issue when designing for direct cooling of power electronics. If the liquid level drops significantly in the load or dry-out occurs, the benefit of two-phase cooling is lost. Superheated vapor is produced in the area surrounding the electronics or motor windings, which results in significantly reduced heat transfer and rapidly increasing junction temperatures in the silicon power devices.

In order to correct these problems, four major revisions were implemented:

1. Move check valve downstream of the oil separator in a horizontal position: This was primarily done to prevent liquid refrigerant migration into the oil separator and to remove an oil trap that occurred next to the check valve. The oil separator was in a reasonably cool area and was acting as a pseudo condenser under certain conditions, and thus drawing liquid from the proper locations in the system.
2. Move the solenoid valve closer to the condenser outlet: The relocation of the solenoid valve was done to remove a large liquid refrigerant zone between the condenser and the expansion orifice in the AC system.
3. Move the evaporator fan to blow out of the case instead of through the condenser and add dedicated condenser fans (Figure 6): The evaporator fan was originally providing the cooling load to the AC system, and this air stream was also used to supply the condenser. The evaporator fan did not supply enough air flow for the condenser to operate properly. When this change was made, external condenser fans were added, allowing better airflow for the condenser, and enabling separate cooling and pressure control for the condenser.
4. Move the pump position within the floating loop to a position upstream of the filter and flow meter: This was done to improve the subcooling into the filter and flow meter which had been experiencing some flashing due to pressure drop across those components. When the pump was pulling liquid through these components, the local refrigerant pressure tended to drop below saturation condition causing flash boiling.

In implementing these changes, the loop design is reconfigured slightly from the layout seen previously in Figure 7, with the new configuration being shown in Figure 8.

During the time period of these system upgrades, the original pump also began to show signs of performance drop due to unrelated pump motor electrical issues, and these issues were resolved simply with a replacement pump.

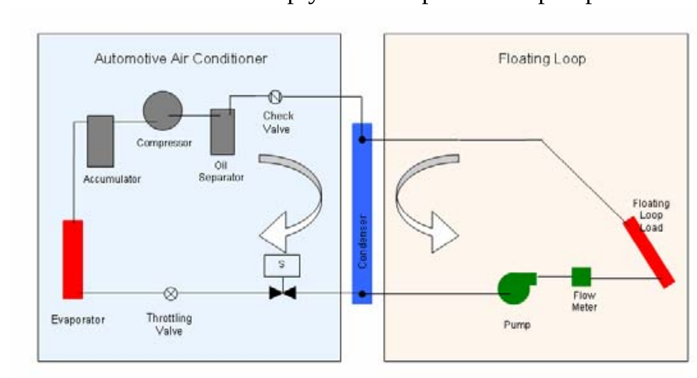


Figure 8: Floating-loop/AC schematic with revisions.

One major design challenge involved the electrical feed-through connections to the loop pump. ORNL is evaluating these issues, as well as looking at commercially available technologies for electrical controls and power feed-throughs. For this stage of the concept testing, a new pump was installed, and power fed to it through commercially procured high pressure electrical feed-through terminals.

4. Results

The system was retested at 1 kW, 1.5 kW, and 2 kW. The 1 kW load had similar results as previous tests. Repeated tests of the cooling loop by itself resulted in maintaining the load temperature around 35°C with ~1.5 kW of heat. Table 1 shows a grouping of the test results from the Case (a), (b), and (c) tests.

The AC unit was incorporated with the loop-test load at 1 kW and at 1.5 kW, and the load was maintained at 37°C and 41°C, respectively. This slightly higher temperature was expected because of the increase in operating pressure, and thus higher saturation temperature at the condenser. The flash boiling effects were minimal during these tests and no risk of load dry out was apparent. The pump was operated at full power during these tests. When the floating loop (loaded at l.5 kW) was decoupled from the AC system, the subsystem temperature returned to 34°C.

EXPERIMENTAL RESULTS

Test Description	Power Level	Condenser Temp
Original Loop-only configuration (Figure 5)		
loop only	2.1 kW	80 C
Combined Loop and AC system Configuration (Figure 7)		
loop only (but connected to AC system)	1 kW	30 C
both systems operating together	1 kW	40 C
Combined Loop and AC systems with upgrades (Figure 8)		
loop only	1 kW	30 C
	1.5 kW	35 C
	2.0 kW	38 C
both systems	1 kW	37 C
	1.5 kW	41 C
	2.0 kW	49 C

Table 1: Experimental results for various floating-loop configurations and test runs.

For test runs up to 1960 W, the floating-cooling loop maintained the load near 38°C. When the AC was coupled to the loop, the system continued to run well with the load surface temperature at 49°C with full pump power. When the AC was turned off, the flash boiling effects appeared to be minimal. The main result of testing with these different configurations is to show that the system runs properly and is easily controllable under all of the possible modes of operation of the combined floating loop and AC system.

5. Conclusions

A heat load placed in parallel with the existing evaporator/compressor arrangement can be adequately cooled with several kilowatts of electronic heat load in a two-phase floating-loop cooling system.

The floating loop can operate as an independent loop or in conjunction with the automotive AC system. The concept is not dependent on using R134a refrigerant, but can use other refrigerants as well. In addition, the cooling concept can be applied as an independent system separate from the automotive AC system if a certain application requires this.

This cooling technique is suitable for full hybrid, hybrid assist, and fuel-cell vehicle configurations.

System capacity is easily scalable for larger loads such as hybrid-electric drives on larger vehicles.

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