Fundamentals of a Floating Refrigerant Loop Concept Based on R-134a 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 issues associated with hybrid vehicles. Removal of the heat generated from electrical losses in traction motors and their associated 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*, and patent pending *Floating Loop System for Cooling Integrated Motors and Inverters Using Hot Liquid Refrigerant.* The floating loop system provides a large coefficient of performance (COP) for hybrid drive component cooling. This loop, which uses R-134a, shares a vehicle's existing air conditioning condenser which dissipates waste heat to the ambient air. Because the temperature requirements for power electronics and electric machines are not as low as passenger compartment air, this adjoining loop can operate on the high pressure side of the existing air conditioning (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 low pressure drop.

Currently hybrid electric vehicles (HEVs) use several different methods to cool the power electronics and hybrid drive components. Other benchmarking work done by ORNL revealed current cooling schemes by leading manufacturers and include 50/50 ethylene-glycol/water heat sinks, forced and natural air convection, and oil circulation. While effective, the liquid sinks operate at a liquid temperature of 65°C [1]. At junction temperatures of 125°C, the silicon in electronic devices begins to break down. Furthermore, the windings in the motor(s) must be kept within the 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 resistance losses in the windings.

The floating loop is a novel approach to the heat removal problem. It takes advantage of R-134a's dielectric properties and also works well in compact heat exchangers which could be used to cool larger structures like a motor housing. Previous work at ORNL demonstrated very

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good dielectric nature of R-134a. Life tests with capacitors, an IGBT, and a gate driver circuit showed no adverse affects when in direct contact with the refrigerant. The life tests have been conducted over a period of 15 months, with periodic functional tests of the circuitry and visual inspections of the components and wiring occurring about monthly.

To date, the floating loop test prototype has successfully removed 2 kW of heat load in a 9 kW automobile AC system with and without the automotive AC system running. The COP for the system as tested ranges from 40-45. The estimated required waste heat load for a typical sport utility vehicle is 5.5 kW and the existing system should be easily scaleable to this larger load. This report mainly focuses on the fundamental proof of concept. A companion paper will address operating conditions and control scenarios encountered during the development of the floating loop.

To prove the concept, three main project goals were set. The first step was to show that a significant heat load could be removed with no compressor. The refrigerant would be moved in the system with a pump or fan, which requires minimal input power.

The second step was to attach a similar loop to an automotive AC system where the loop and AC system would share the condenser. The objective of the second goal was to prove the loop could share the condenser without adversely affecting the inventory behavior or performance of the automotive air conditioner.

The last goal was to operate the floating loop and AC simultaneously. This test would be indicative of normal operation of the floating loop in a full hybrid configuration.

Initial Results

The first goal was proven with a bench top setup consisting of a pump, heat source, and condenser. This cooling loop removed more than 2.1 kW of heat load with minimal input power. A pump was used with input power of 48 W. The cooling loop resulted in a COP of 44.

For the second set up, a loop was attached to the high-pressure condenser section of a commercially available automotive AC system from a full size sedan with a 9 kW capacity (Fig. 1). The loop inlet line was placed at the lowest possible attachment point to ensure the pump would be supplied with liquid without undue increases in system inventory. A 1 kW test load was initially used to prove loop operation. The loop maintained the test load near 30°C. This specific system could also have handled a larger load, but these tests were not necessary for proof-of-concept (POC).

After running, the loop was isolated from the stock AC system. The AC system produced adequate cooling after this test, which showed the loop had no adverse affect on AC system refrigerant inventory behavior.

The 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, as compared to the loop-only scenario, is a result of the increase in condenser saturation pressure when the compressor is running. One key element in obtaining these stable results was to provide increased air flow across the condenser.

Design Evaluation

Overall, the floating-loop system met the initial design goals; however, these tests revealed several issues with the loop/AC dynamics. Oil traps and refrigerant traps had been unintentionally created during the integration of the loop into the automotive AC system. Inventory surging during the cycling of the compressor was also a problem. Dry out of the load 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, loss of two-phase cooling occurs and superheated vapor is produced, which results in rapidly increasing junction temperatures. These control issues will be addressed more thoroughly in another paper.

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

1. Move check valve downstream of the oil separator in a horizontal position.
2. Move the solenoid valve closer to the condenser outlet.
3. Move the evaporator fan to blow out of the case instead of through the condenser. Add dedicated condenser fans.
4. Move the pump position within the loop to upstream of the filter and flow meter.

Final Results

After implementing these changes, the loop shown in Fig. 2 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.

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. The surging dynamics appeared stable during these tests and no risk of load dry out was obvious. The pump was at full power during these operations. When the l.5 kW load was decoupled from the AC system, the floating-cooling loop returned to 34°C.

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 at 49°C with full pump power. When the AC was turned off, the system dynamics appeared to be stable.

Conclusions

A heat load placed in parallel with the existing evaporator/compressor arrangement can adequately cool several kilowatts of electronic heat load.

The floating loop can operate as an independent loop or in conjunction with the automotive AC system.

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

For operation as part of a 9 kW automobile cooling system, the ORNL floating-loop system has been proven to function well at 2 kW, with a very attractive COP.

System capacity is easily scalable for larger loads.

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References

1. Toyota Motor Corporation, *Prius New Car Features 2004*, ppTH-34 NHW20 series Pub No. NCF255U, 2004.
2. J. S. Hsu et al., *Floating Loop System for Cooling Integrated Motors and Inverters Using Hot Liquid Refrigerant*, U.S. Patent Application 20050178148, Disclosure #1300001378, filed August 25, 2004.
3. J. S. Hsu et al., *Total Thermal Management System for Hybrid and Full Electric Vehicles*, U.S Patent 6,772,603, August 20, 2004.
4. J. S. Hsu et al., *Cascaded Die Mountings with Special-loaded Contact-bond Options*, U. S. Patent 6,930,385, August 16, 2005.
5. J. B. Campbell, L. M. Tolbert, C. W. Ayers, B. Ozpineci, "Two-Phase Cooling Method Using R134a Refrigerant to Cool Power Electronics Devices", *Applied Power Electronics Conference (APEC 2005)*, MAR 6-10, 2005, pp. 141-147.

Fig. 1. Floating loop attached to full sized sedan AC system in a cabinet.

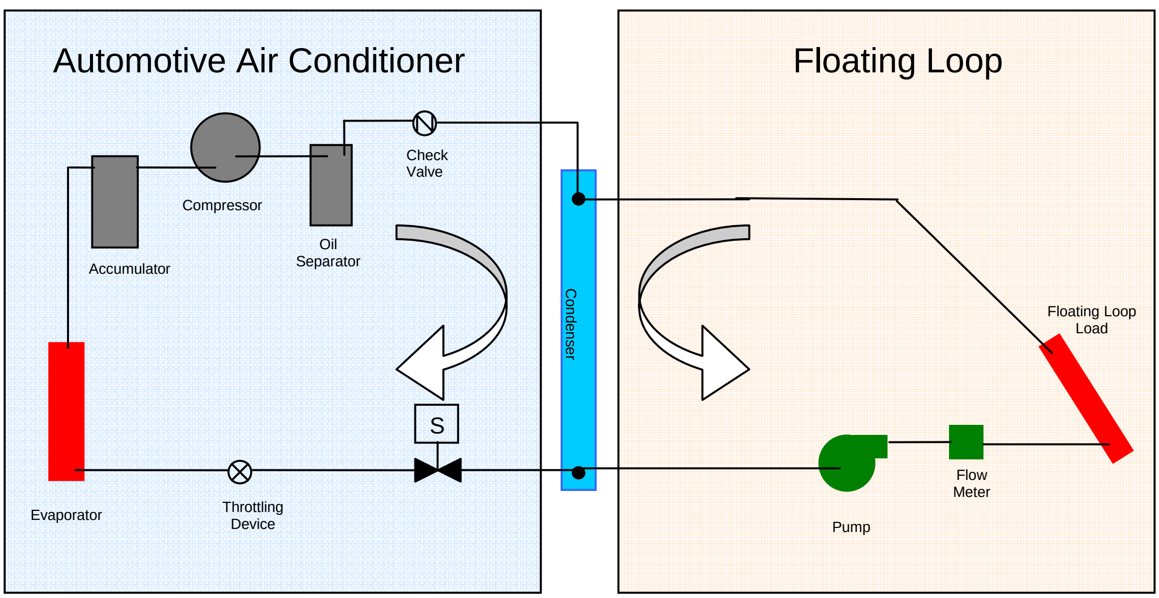

Fig. 2. Floating loop/AC schematic.