# Operating Controls and Dynamics for Floating Refrigerant Loop for 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. This work is part of the ongoing FreedomCAR and Vehicle Technologies (FCVT) program, 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 drive component cooling. This loop uses R-134a as a coolant and shares the vehicle's existing air-conditioning (AC) condenser, which dissipates waste heat to the ambient air. Because temperature requirements for cooling 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 a compressor and requires only 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 should also, ideally, provide a high COP, a flat temperature profile, and low pressure drop.

To date, the floating-loop test prototype has successfully removed 2 kW of heat load in a 9 kW automobile passenger AC system with and without the automotive AC system running. However, during the cyclic operation of the floating refrigerant loop, some two-phase transient behavior is evident. In order to maintain stable running conditions, specific operating controls were implemented. Also thermodynamic energy balances were conducted to further analyze the operating conditions.

**Keywords**

Direct Cooling, Refrigerant, Thermal Management, High Heat Flux Electronics, Floating Loop

## 1. Background

Current hybrid electric vehicles (HEVs) employ different methods to cool the power electronics and hybrid-drive components. Cooling schemes by leading manufacturers include the use of 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 [3] for vehicles using a separate radiator, and 100–105°C when using the engine radiator. At junction temperatures of 125°C, the silicon in power electronics devices begins to lose reliability, and at 150°C the device 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. However, with improved cooling, the motor can run at a higher efficiency due to decreased resistance 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 ethylene-glycol/water internal combustion engine (ICE) cooling system (105°C), transmission oil flowing through a separate cooler (85°C), and the passenger compartment AC refrigerant system (currently R134a refrigerant at about 60°C).

The floating loop is a novel approach to the heat removal problem. It takes advantage of the R-134a dielectric properties and temperature ranges, works well in compact heat exchangers, and could be used to cool larger structures such as a motor housing. Previous work at ORNL demonstrated the superior dielectric nature of R-134a. Life tests, which measure a device's ability to retain its published specifications over time, have been conducted with capacitors, insulated gate bipolar transistors (IGBT), and a gate-driver printed circuit board in direct contact with the refrigerant. The life tests have been conducted over a period of 21 months, with periodic visual and functional testing [4]. No adverse affects on the components have been detected.

The implementation of this type of cooling for the electronics as compared to oil paths, convective air, or ethylene glycol mixtures allows for lower junction temperatures to be maintained. Other research shows that lower junction temperatures result in higher efficiencies for

* Prepared by Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U.S. Dept. of Energy under contract DE-AC05-00OR22725. The submitted manuscript has been authored by a contractor of the U.S. Government under contract DE-AC05-00OR22725. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

the motor and controls due to decreased resistance losses. With electronic components operating at higher efficiencies, fewer and smaller devices can be used. Ultimately, the development of the floating loop is the first step by ORNL in shrinking the size of the traction drive and its associated high heat flux electronics while maintaining net power output [5].

A previous paper [6] details the development process for the floating loop. Figure 1 shows schematically the layout of ORNL's floating loop. An adjoining loop shares the condenser with the existing automotive AC. High-pressure liquid exits the condenser and enters the loop. The use of the hotter refrigerant is possible because the temperature demands of the electronics are not as strenuous as that of the passenger compartment. The subcooled refrigerant is pumped through the loop and reenters the condenser after the automotive AC compressor at some quality below 100%, which implies the refrigerant contains some liquid and is not entirely vapor. In this test configuration, a resistive heat load was used to simulate the waste heat of a motor and its associated electronics.

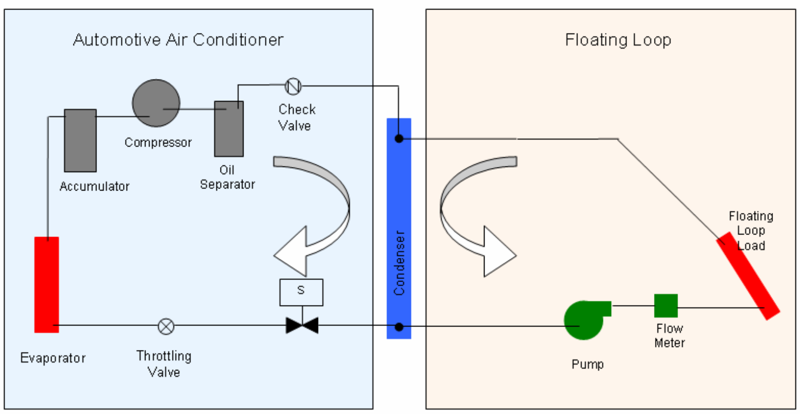


**Figure 1: Schematic of current AC/Floating Refrigerant Loop**

The COP for the tested floating loop system ranges from 40 to 45, as compared to a typical AC system COP of about 2 to 4. The estimated required waste-heat load for future hybrid applications is 5.5 kW, and the existing system can be easily scaled to this larger load.

## 2. Design Evaluation

The initial design met the prototype goals; however, these tests revealed several issues with the loop/AC dynamics. Oil traps and liquid refrigerant traps had been unintentionally created during the integration of the loop into the automotive AC system. Liquid migration and flash boiling during the cycling of the compressor was also discovered to be 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 significantly reduced heat transfer and rapidly increasing junction temperatures.

Two-phase cooling is crucial to the overall goal of the floating loop. The refrigerant loop provides increased cooling so that the required number and size of silicon dies for the inverter are decreased. In this configuration without two phase cooling, the electronics would quickly overheat causing inverter failure.

In order to correct these problems, revisions were implemented and are reflected in Figure 1. During these changes the original pump also began to show signs of performance drop due to unrelated pump motor electrical issues. One major design challenge had also been the electrical connections to the pump. A new pump was installed with commercially available high pressure electrical terminals, which alleviated the problems.

## 3. System Dynamics and Operating Conditions

In order to assure a more robust design, the system instabilities previously mentioned were examined. When the pump was not at full power, several modes of system failure could arise: the pump would not supply enough liquid refrigerant to the loop in order to keep it wet, the differential pressure across the loop would collapse and cause backflow, or the cycling of the compressor would cause dry-out due to liquid migration. During typical loop operation with an ambient temperature of 22°C, four operating scenarios were encountered. These operating conditions are discussed individually to better understand their effects on the system behavior.

The four operating scenarios are: steady operation of the floating loop without the AC, steady operation with automotive AC, transient start up of automotive AC with loop, and the cycling off of the automotive air while maintaining loop operation. Each case presents unique operating requirements for which control methods are proposed and future design issues are discussed.

### 3.1. Steady Operation of the Floating Loop

The first operating condition is for the continuous operation of the floating loop with no automotive AC. In this mode, the automotive AC system is isolated via a solenoid valve and check valve. It is crucial to locate the valves as close as possible to where the loop attaches to the system. Extra piping on the liquid side will increase the required refrigerant inventory. Also the check valves placement sufficiently influences this operating condition. Prior to the design evaluation, the oil separator was isolated with the loop because of assembly issues. The oil separator created refrigerant traps and oil traps on the loop outlet/condenser inlet side of the system and allowed excessive amounts of oil into the floating loop. With replacement of the valves steady operation was achieved.

Testing conducted resulted in the resistive load being maintained between 35–40°C with system pressures around 1 MPa. In this condition, the loop runs stable, provided enough initial inventory is present in the loop.

### 3.2. Steady Operation of Loop and Automotive AC

The second operating condition occurs when the loop and automotive AC operate simultaneously in a steady state.

When the compressor is engaged, the solenoid opens and both systems use the condenser. As long as loop inventory is maintained via the auxiliary pump, no problems arise. If the pump stalls, the risk for back flow and dry-out in the loop arises. Even with the additional heat loads of 2 kW from the floating loop, the passenger air temperature was near 12°C with an ambient temperature near 25°C.

During the operation of both systems, the possibility exists that liquid refrigerant could enter the suction side of the compressor, especially if the correct inventory balance between the loop and AC system is not maintained. Factors contributing to this state could be the result of an overcharged air conditioner, an undercharged AC and overcharged loop, or an overcharged AC and loop. This potentially catastrophic scenario has been addressed with loop controls to prevent liquid flood back.

### 3.3. Transient Start-up of Automotive AC with Loop

The third operating condition is the initial transient when the compressor is engaged. During this transient, the compressor initiates the flow in the automotive AC path and the solenoid opens. The transient lasts for 30–40 seconds. During this time, the automotive system is establishing the pressure differential between the condenser and evaporator. Because of the increase in saturation pressure of the condenser, the adjoining loop also increases in pressure while maintaining relative constant temperature, which results in additional liquid in the loop and subcooling at the load inlet. The temporary extra liquid inventory insures that the floating loop load will not dry-out during this transient. The loop liquid pump, however, needs to develop sufficient pressure rise to prevent loop backflow.

### 3.4. Transient Shut-down of Automotive AC with Loop

Although the onset of the compressor operation does not adversely affect the performance of the floating loop, the cycling off of the compressor causes the liquid inventory in the loop to decrease because of the condenser pressure decrease. This transient represents the last control scenario. Because the solenoid valve isolates the compressor, the balance of liquid and vapor inventory within the loop shifts and some flash boiling occurs.

The drop in pressure reduces the subcooling in the loop which induces flash boiling. The thermal inertia of the load maintains the flash boiling until the temperature is sufficiently reduced. If the loop-heat load and pump flow are appropriately scaled, then the loop-inventory level will decrease to the previous loop-operating levels. Otherwise, the potential risk for load dry-out arises.

### 3.5. Control Methods

Because of the potentially undesirable dry-out of this last operating scenario, several control solutions were proposed. The first was to operate the compressor with a variable-speed motor drive. The speed and thus the volumetric flow of the compressor could then be controlled. By ramping the compressor power down, the pressure could fall slower and more in line with the temperature profile. This operation would decrease the amount of flash boiling and preserve a wetted load. In practice, this method was not viable with the components in our cabinet system. This control method needs to be further investigated with different valving, an electric compressor, and a variable-speed drive.

The other control solution was to manually close the solenoid valve prior to compressor shut down. This operation avoids dry-out conditions by overcharging the floating loop. With the solenoid closed, the compressor continues to feed inventory to the condenser and loop for a few seconds. This extra inventory at higher pressure is just enough to allow for the transient to occur without drying out the load. For the remaining tests with the floating-loop configuration, this control method was followed.

A method that controls this behavior automatically is preferred. Tests have shown that the dry-out occurs under the vapor dome of R-134a. Thus, no temperature or pressure indications are evident from the refrigerant during dry-out. Only when the refrigerant moves into the superheated phase do measurable indicators begin to appear. Pressure and temperature respond asymptotically. By this time counteracting the dry-out becomes harder because of the instability of the system.

To date visual sight glasses have been used to qualify the dry-out state. This method works but could be improved. Automatic switching is being developed to address this issue.

### 3.6. Thermodynamic System Behavior

In any system, it is desirable to understand the performance not only from an empirical view but also from the fundamental physics. In this case, that understanding can come from a thermodynamic study of the automotive AC system and floating loop. This analysis was meant to clarify the basic operation of the loop. Basic instrumentation and several simplifying assumptions, including a constant-pressure condenser and evaporator, were used to produce this initial study.

Figure 2 depicts the measured behavior in the form of a Pressure-Enthalpy (P-h) diagram. Operating conditions shown are the AC system by itself (blue), and the combined floating loop and AC system (green and red). The separate heat flows out of the condenser and into the evaporator were obtained from air-side calculations and psychrometric measurements.

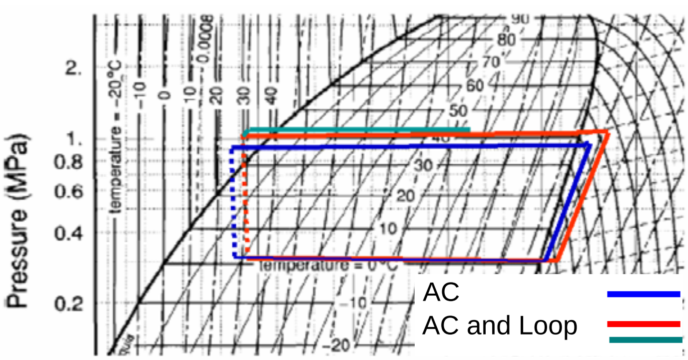


**Figure 2: P-h diagram of refrigeration cycles.**

Condensate was also collected for confirmation by calculating the latent heat required to produce the measured amount of condensate. Various temperatures and pressures were used to determine compressor, condenser, evaporator, and floating-loop operating ranges. Detailed pressure drops and extensive calibrations were not performed for this analysis.

The baseline for the AC system (blue) is a normal refrigeration vapor-compression cycle. The cycle does show from the P-h diagram that the cabinet AC system was most likely low on inventory. Ideally, little or no superheat would be present at the exit of the evaporator and more subcooling, 10–15°C, would be at the output of the condenser.

The combined system P-h diagram (red and green) also follows some of the same trends. The shift to the right indicates low inventory in the AC system. Ideally, the evaporator pressure would not change between the two operating scenarios, which the measurements confirmed. The addition of the loop increased the load on the condenser, which increased operating pressure with a constant air flow maintained. Calculations showed the baseline condenser load (AC only) was 4.2 kW and the combined condenser load (AC and loop) was 5.5 kW. The floating loop additional load (pump and resistive load) was 1.1 kW. These results indicate 5% error.

The green floating loop path is missing some detail. Because of the physical set up, the loop flow should reenter near the condenser inlet. A mixing body which receives superheated vapor from the compressor and a refrigerant quality from the loop is not distinctly evident on this chart. More instrumentation is necessary to exactly determine the nature of this process.

Figure 3 shows the difference between operation of the floating loop as an isolated system and the floating loop working in conjunction with the automotive AC system. As mentioned previously, the coincident operation of the systems results in an increase in condenser and loop pressure.

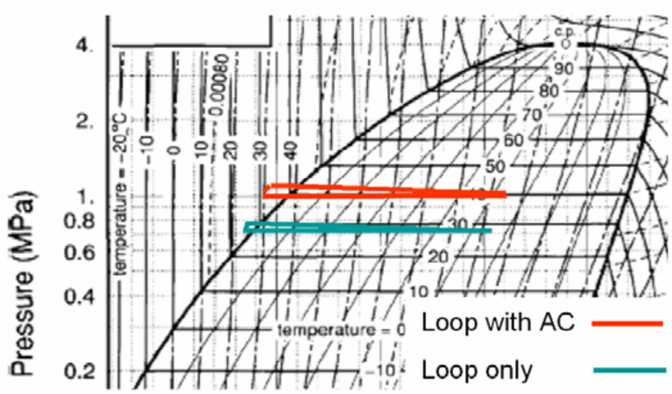


**Figure 3: P-h diagram of floating-loop operations.**

The loop starts with subcooled liquid from the condenser. In these cases, the degree of subcooled liquid is subject to system charge. The red loop would have more subcooling with more total system inventory. Increasing the total system inventory would increase the condenser inventory, which would increase the loop inventory. Thus the isolated loop would start with more degrees of subcooling.

The resistive-heat load and the energy calculated from loop-liquid flow rates were comparable. This result is supported by the consistent enthalpy change seen between the two cases.

## 4. Conclusions

A heat load placed in parallel with the condenser of a typical automotive air conditioning system can adequately cool several kilowatts of electronic heat load, which is applicable for full hybrid, hybrid assist, and fuel-cell vehicle configurations.

The operation of the floating loop results in four major running scenarios. Each one has the potential to run stably and reliably subject to appropriate component sizing and controls.

A solenoid valve located close to the loop supply/condenser outlet to isolate the passenger AC components is crucial to the stable operation of the floating-cooling loop during AC compressor shutoff.

Methods of increasing liquid inventory in the condenser and floating loop are required to maintain a wet load during compressor transients.

## Acknowledgments

Special thanks to Susan Rogers with the Department of Energy for the support of this research work.

In the Power Electronics and Electric Machinery group we would like to recognize all the hard work supporting the floating loop research and development by Chester Coomer, Marshall McFee, Mike Jenkins, and Steve Campbell. They were instrumental in supporting fabrication and testing work throughout the project. Also special thanks to Dr. Jim Conklin for recommendations related to refrigeration loops and properties.

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