Abstract

Removal of the heat generated from electrical losses in traction motors and their associated power electronics (PEs) is essential for the reliable operation of motors and PEs. 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 PEs 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.

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 behaviour 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.

Objective

The purpose of this study was to better understand the operating dynamics of Oak Ridge National Laboratory's (ORNL) patented floating-refrigerant loop for high-heat flux electronics. Other goals included investigation of transient controls and thermodynamic behaviour of the system.

Equipment and Procedure

After prototype testing, a floating-refrigerant loop was attached to a 9 kW automotive AC system. A resistive-heat load was attached to the high-pressure loop to simulate the waste-heat load of an inverter and traction motor. The loop parallels the condenser. The set up is shown in Fig. 1.

The temperature and pressure were measured at the loop inlet and outlet and at the load inlet. Temperatures were also recorded on the resistive load. Necessary data needed for first law energy analysis of the AC system was also collected.

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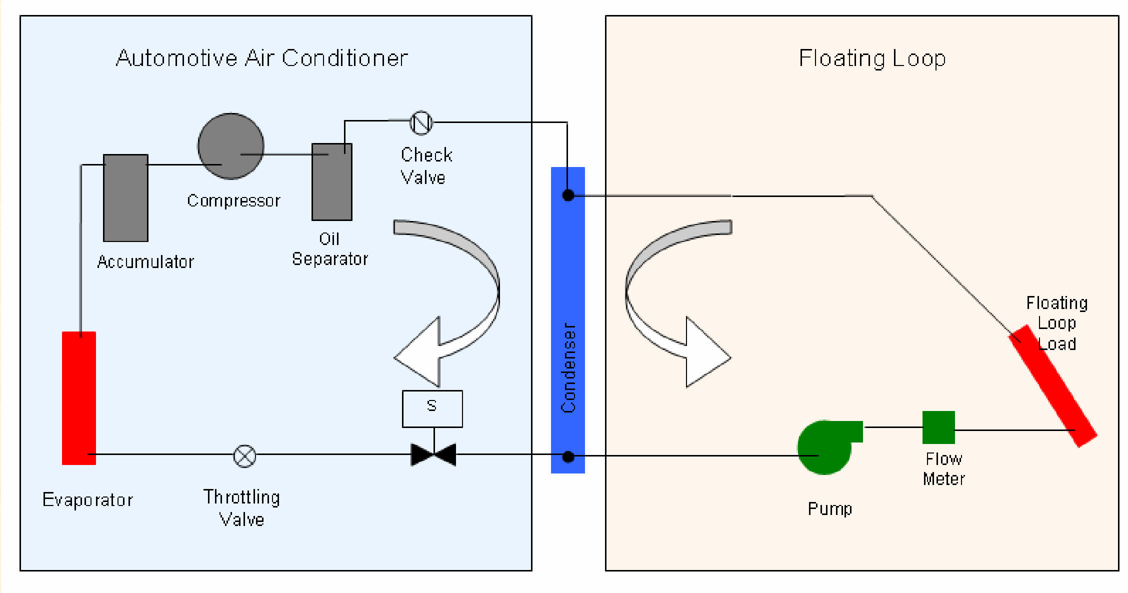

Fig. 1. Schematic of AC/refrigerant-floating loop.

Operating Conditions

- Steady Operation of Floating Loop
  - Stable
    - initial inventory sufficient
    - pump establishes pressure differential
- Steady Operation of AC and Floating Loop
  - Overall stable
  - Instabilities
    - dependent on pressure increase across pump
    - some inventory migration to AC
    - possibility for flooded compressor
- Transient Start-Up of AC with Loop
  - Pressure drop across orifice established
  - Stable
    - inventory shift to saturated liquid
    - additional subcooling to loop
- Transient Shut-Down of AC with Loop
  - Instabilities possible
    - flash boiling due to rapid pressure decrease
    - thermal inertia holds load above saturation temperature

Operating Controls

- Steady Operation of AC and Floating Loop
  - Inventory balance in AC monitored by automatic valving to prevent liquid at inlet of compressor
  - Other switching controls liquid level in the floating-loop load to insure flooded PEs
- Transient Shut-Down of AC with Loop
  - Add solenoid close to the condenser outlet
  - Prior to compressor shut-down, close solenoid while the with compressor is running
    - increase loop liquid inventory
    - provides sacrificial inventory for flash boiling
      - PEs remain flooded

Thermodynamic Behavior

- Constant pressure evaporator and condenser assumed for initial analysis
- Pressure increase in loop due to condenser operating pressure (Fig. 2)
- Load does not cause refrigerant to go to 100% vapor
- The AC P-h diagram, Fig. 3, shows more superheat at the compressor inlet when the loop is running
  - Ideally the blue and red cycles should overlap. The difference indicates low inventory.

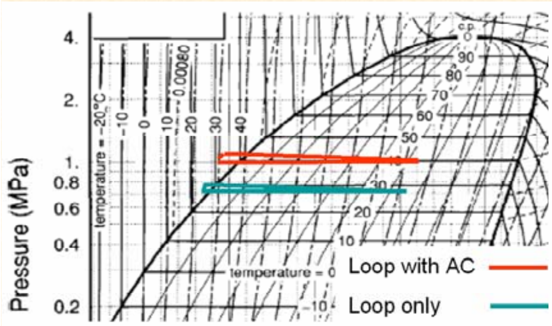

Fig. 2. P-h diagram of loop operation.

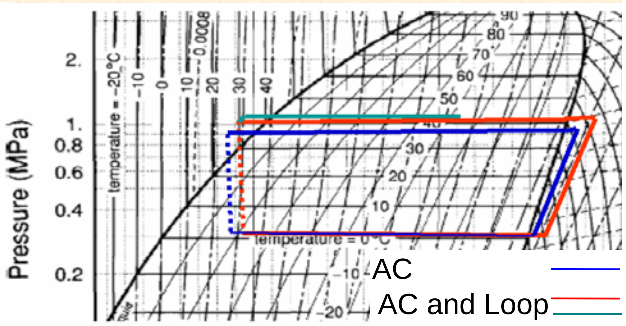

Fig. 3. P-h diagram of AC system.

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- The higher condenser pressure reflects the additional load of the loop.
- Unknown dynamics occur during mixing of loop outlet and condenser inlet
  - Green loop cycle should at least extend to saturated vapor line.

Future Work

- Incorporate real inverter loads to loop
  - Instrument more to get a better approximation of thermodynamic behaviour.
- Test at other ambient temperature to examine stability of system.

Acknowledgments

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References

J. S. Hsu et al., *Total Thermal Management System for Hybrid and Full Electric Vehicles*, U.S Patent 6,772,603, August 20, 2004.

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.

Toyota Motor Corporation, *Prius New Car Features 2004*, pp. TH-34.

J. B. Campbell, L. M. Tolbert, C. W. Ayers, and B. Ozpineci, "Two-Phase Cooling Method Using R134a Refrigerant to Cool Power Electronics Devices," pp. 141–147 in *Proceedings of Applied Power Electronics Conference,* 2005.

J. S. Hsu et al., *Cascaded Die Mountings with Special-loaded Contact-Bond Option*, U.S. Patent 6,930,385, August 16, 2005.

C. W. Ayers, J. S. Hsu, and K. T. Lowe, "Fundamentals of a Floating Loop Concept Based on R134a Refrigerant Cooling of High Heat Flux Electronics," Semi-Therm 22, 2006.