HYBRID LOOP THERMAL BUS TECHNOLOGY FOR VEHICLE THERMAL MANAGEMENT

Chanwoo Park and Jon Zuo
Advanced Cooling Technologies, Inc., Lancaster, PA

Paul Rogers and Jeffery Perez
U.S. Army TACOM, Warren, MI

ABSTRACT

Army's next generation vehicles require more electric and electronic devices with increasing power density for improved multi-functionality. The increasing waste heat from these devices will present great challenges to the capabilities of conventional air/liquid cooling systems in cooling multiple, high heat flux sources dispersed over the entire vehicle. In this paper, a high performance hybrid loop thermal bus technology for vehicle thermal management is presented. The technology combines the robust operation of pumped two-phase flow cooling with the simplicity of capillary flow management. The test results show that the hybrid loop thermal bus can manage multiple high heat flux heat sources during the startup and transient heat input operation with no coolant flow control.

1. INTRODUCTION

Army's next generation vehicle, Future Combat System (FCS) will have more electric and electronic systems with increased power density for multi-functionality and multi-mission. The "drive-by-wire" trend will increasingly replace current mechanical and hydraulic actuators with electrical ones. The increasing waste heat from these electrical devices will present great challenges to the capabilities of conventional air/liquid cooling systems in cooling multiple, high heat flux sources dispersed over the entire vehicle (Park and Jaura, 2002).

The FCS Environmental Control System employs a cooling system having an air cooling loop for low heat flux dissipating electronics and a liquid cooling loop for high heat flux dissipating devices. The vapor compression system is used to dissipate the heat from the electronics to ambient. The liquid cooling loop requires a large coolant flow rate to limit maximum coolant temperature rise in cold plate micro-channels of high heat flux devices (Garimella and Singhal, 2003). The large coolant pumping requirement results in a bulky and heavy and more fuel-consuming system.

In contrast, a two-phase system has fundamental advantages over the conventional single-phase liquid cooling system. One of the advantages is due to the large heat transfer coefficient. The boiling heat transfer coefficient due to film boiling ranges from 10,000~100,000W/m^2-^{o}C which is one order of magnitude larger than the convective heat transfer coefficient of conventional liquid cold plates. The larger heat transfer coefficient directly corresponds to a smaller thermal resistance and consequently high heat flux cooling capability.

Another advantage of the two-phase cooling system is due to large latent heat during evaporation. The latent heat could be typically two orders of magnitude larger than the sensible heat of a similarly-sized single-phase cooling system. Therefore, the two-phase system requires much less coolant flow contributing to a smaller pump and a more compact cooling system. Furthermore, the high flux cooling capability coupled with isothermal evaporation will greatly increase the reliability of electronic systems, because any temperature non-uniformity in silicon chips will cause thermal stresses and reduce their reliability.

2. HYBRID LOOP THERMAL BUS

Thermal Bus is conceptually analogous to an electrical bus. The thermal bus transports thermal energy as the electrical bus transports electrical energy. With the rapidly evolving "intelligent battlefield" concepts, electronic systems are expected to change many times over vehicle lifetime. It makes excellent sense to have a core thermal bus to be a part of the vehicle infrastructure and separated from distributed thermal buses for new electronic subsystems. The distributed thermal buses for the newly updated electronics are simply plugged to the core thermal bus and operate.

The thermal bus technology using a hybrid two-phase cooling loop technology was developed for vehicle thermal management. The hybrid loop uses an active pump to supply liquid to the cold plate (or evaporator). The capillary wick technology is to control the evaporation in the evaporator and the system pressure balance. The evaporator serves as a thermal interface for the distributed thermal bus of the electronic subsystem. The hybrid loop system of pump-assisted capillary liquid management is capable of cooling multiple high heat flux sources.

The hybrid loop thermal bus directly couples the heat dissipating components to the vehicle's radiator, bypassing the air cooling and liquid-phase chiller loop. This provides the greatest thermal performance gains and mass savings by removing overall thermal resistances, however at the expense of an additional radiator. A vehicle system analysis based on FCS Environmental Control System shows the technical merits of the hybrid loop thermal bus technology. The integration of the thermal bus into the ECS reduces the evaporator and condenser heat loads and the compressor power consumption by 47%, 9.6% and 47%, respectively. The condenser airflow and cooling fan power consumption are reduced by 47% and 45% respectively (Zuo and Park, 2004).

Fig.1 shows a prototype hybrid loop thermal bus system which is capable of removing a total heat of 2,500W from five discrete heat sources in 3-dimeniosnal layout. The transient heat fluxes ranges from 188W/cm^2 to 250W/cm^2. The hybrid loop system was successfully tested at various startup and transient conditions, without the need for flow adjustment or control.

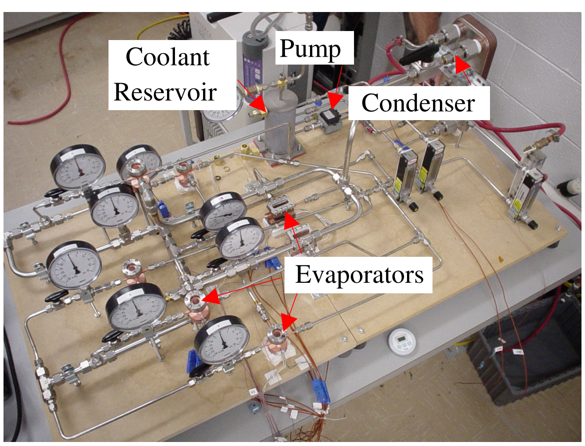

Fig.1 Prototype hybrid loop thermal bus.

ACKNOWLEDGMENTS

The authors wish to acknowledge the contributions of Mr. David Sarraf and Mr. Jay Weaver for their efforts in the design, fabrication and testing of the hybrid loop hardware. This work was performed under Army SBIR Contract No. W56HZV-04-C-0113.

REFERENCE

Park, C. and Jaura A. K., 2002, "Thermal Analysis of Cooling System in Hybrid Electric Vehicles", SAE Transactions, SAE-2002-01-0710.

Zuo, Z. J., and Park, C., 2004 "Thermal bus technology for next generation vehicles", Army SBIR Phase I Final Report, Contract No. W56HZV-04-C-0113, August, 2004.

Garimmela, S. and Singhal, V., 2003, "Single-Phase Flow and Heat Transport in Microchannel Heat Sinks", 1st international Conference on Microchannels and Minichannels, Rochester, NY, April 24-25, 2003.

CONCLUSION

The hybrid loop thermal bus technology was demonstrated for a total heat load of 2,500W at the maximum heat flux of 250W/cm^2. The achievements were summarized as follows:

- Maximum sustainable heat flux from multiple heat sources: Prototype tests demonstrated a total heat input of 2,500W from five heat sources (three heat sources with 250W and two with 944W) at heat fluxes ranging from 188 to 250W/cm^2 over heat source areas of 5cm^2 to 1cm^2 respectively. No dry-out was observed at the maximum power conditions. The evaporators are scalable to have large heat input areas with high heat fluxes using the patented evaporator design.

- Dynamic performance: The heat input was varied between the maximum and minimum values. During the dynamic power testing, no active flow adjustment or control was applied. The loop was robust against transient changes in heat load. It operated successfully over a wide range of conditions with no changes in flow settings.

- Uneven heat loads: This test demonstrated the ability of the hybrid loop to run with varying and asymmetric heat loads into evaporators at different elevations. The loop operated well with no large transients or overshoots upon change in power.