Two-Phase Thermal Management Systems for Space

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Abstract. Active two-phase thermal management systems have been shown to be weight and power effective for space platforms dissipating over 20 kWt of waste heat. A two-phase thermal management system can provide nearly isothermal heat transport at mass flows significantly lower than required for single-phase systems by employing a working fluid's latent heat rather than absorbing the heat sensibly in temperature change. Phase management issues specific to reduced gravity include pump cavitation, loop inventory control and potential dry out in the evaporator. Hamilton Sundstrand has developed and demonstrated in a reduced gravity aircraft environment, a suite of two-phase technologies that manage the liquid-vapor phase distribution. These technologies keep the liquid phase available at the pump inlet for pumping and present at heat acquisition boundaries for evaporation. This paper reviews these technologies for future high power, long duration space platforms.

Keywords: Two-Phase Thermal Management System (TPTMS), Rotating Fluid Management Device (RFMD), Shear Flow Condenser, Swirl Flow Evaporator

INTRODUCTION

Small spacecraft currently employ passive cooling, heat pipes or pumped single-phase loops for heat rejection. Passive loops, such as the capillary pumped loops, provide low-head, capillary driven fluid circulation but are limited by low evaporator burnout heat fluxes, start-up and transient concerns and inventory management issues. However, NASA's vision for long-term space exploration relies on large, long duration, high power level for space platforms and surface operations beyond earth. Thermal management of these platforms requires the transport of large amounts of heat dissipated by various systems, modules and payloads over long distances with minimal power. Additionally, some payloads impose specific temperature regulation requirements. To minimize radiator size and weight, the transport temperature drop, and thereby radiator temperature must be maximized.

Two-Phase Thermal Management Systems (TPTMS) afford low pumping powers due to the reduced flow requirement of latent vs. sensible heat transfer. Temperature change for sensible heat transfer in a single-phase loop is replaced by the nearly isothermal operation of a TPTMS. Reduced coolant flow rates and pump powers also result in lower pump weights and vibration. A robust pumped two-phase system can be designed with gravity-insensitive heat exchangers and pumps that will provide a reliable and flexible solution to thermal management of large heat loads in space applications. An actively pumped two-phase system can efficiently transport large heat loads in small plumbing lines at modest pumping powers. Pumping pressures developed also provide sufficient fluid motivation for gravity-insensitive heat transfer by utilizing curvilinear or shear-driven forces for phase control in evaporation and condensation. The pumped flow loop is also compatible with spray flow evaporators because it provides the necessary liquid subcooling and phase separation of the wet exhaust. The higher velocities and forces developed in these specialized two-phase heat exchangers greatly enhance heat transfer coefficients, thereby minimizing the source-to-sink temperature drops and radiator requirements. Also, phase change heat transfer (evaporation and condensation) can be more effective than single-phase convection, affording the opportunity for heat exchanger size reduction. The objective of this paper is to present the issues of two-phase thermal management in space applications and selected technologies that address these issues.

BASIC ISSUES WITH MICRO-GRAVITY THERMAL MANAGEMENT

The risks specific to two-phase systems for μ-gravity are phase control, phase distribution (i.e., flow regimes), pump cavitation, condenser stability and evaporator dry-out. The most crucial issue in any pumped two-phase system is the maintenance of Net Positive Suction Head (NPSH) required by the pump to avoid cavitation. With two-phase return flows, saturation pressure control and fluid inventory issues are closely related to the pump NPSH maintenance. Phase control issues are important in the heat transfer devices. Wet-wall boiling must be guaranteed in zero-gravity conditions and positive condenser pressure drops must be maintained for inventory control and stable operation in condensation. Any two-phase loop concept that controls flow to match heat load by limiting or eliminating liquid carry-over through the evaporator faces the difficult task of sensing vapor quality or dry-out excursions. The suggested approach intrinsically avoids this issue by its passive flow control with designed two-phase return flows from the evaporators.

Hamilton Sundstrand's design philosophy for low and adverse g-environments is to build components and systems that are g-insensitive. With this strategy, components can be tested in all orientations with respect to gravity for higher confidence in μ-gravity operation. The design approach mitigates the effects of reduced or adverse gravity on two-phase flow and phase change phenomena by providing induced fields, either by swirl, shear-driven or centrifugal forces.

LOOP DESCRIPTION

The Two-Phase Thermal Management System (TPTMS) consists of two loops both driven by the Rotating Fluid Management Device (RFMD). This approach, first published by Bland et al. (1985), is shown schematically in Figure 1A and Figure 1B, slightly subcooled liquid is provided to all the heat source evaporators in parallel, where a portion of the flow is evaporated. For temperature control and high heat transfer rates, wet-wall boiling is maintained in the evaporators. The two-phase return flows are separated in a device that pumps the liquid back to the evaporators and the vapor to the condenser. The condensate return from the condenser is pumped and then sprayed in the RFMD to the warm saturation conditions.

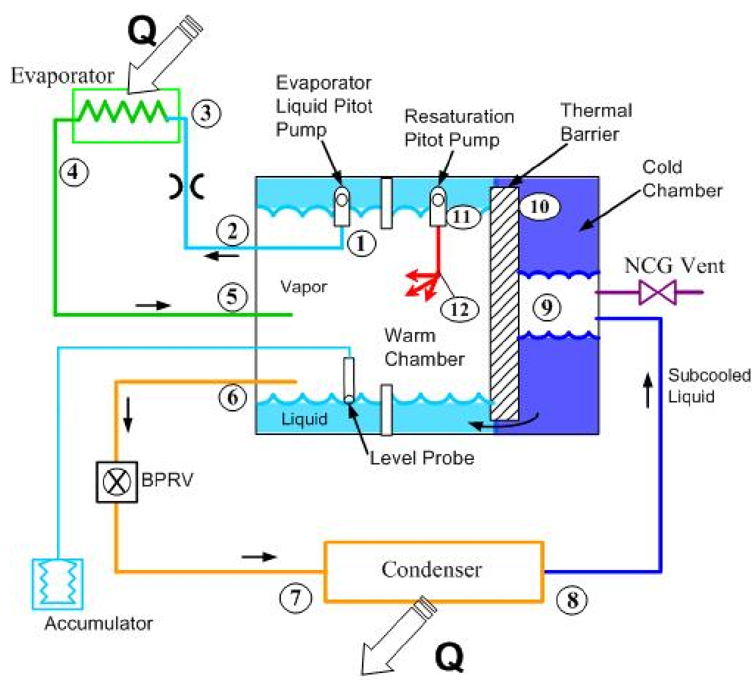

FIGURE 1A. Two-Phase Thermal Management System Schematic.

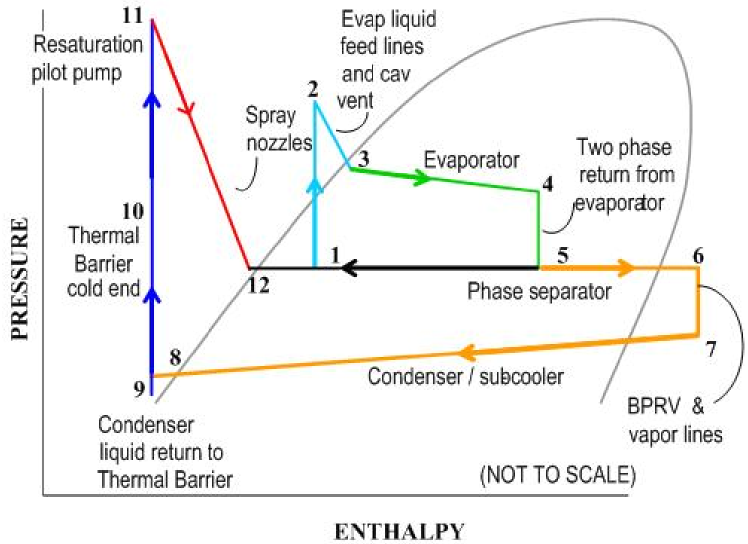

FIGURE 1B. Two-Phase Thermal Management System State Diagram.

Loop temperature is maintained by controlling the pressure in the warm cavity of the RFMD. Temperature control is thereby accomplished because saturation conditions of the liquid interface are maintained by extensive direct liquid-vapor contact in the RFMD spray. Pressure control has been demonstrated by a self-activated, passive control pressure regulator, and by both hydraulically and electrically modulated devices run off pressure sensors. The fluid inventory in the loop will vary with heat load due to changes in the evaporator outlet quality and line void fractions. At maximum heat load the condensation will occur over most of the flow length in the condenser whereas the condensing length becomes shorter at reduced load, thereby changing the liquid inventory in the condenser. The excess liquid inventory is accommodated by a loop accumulator referenced to the RFMD warm side. The fluid level in the warm side is controlled by the accumulator level probe. If fluid inventory should start to increase in the RFMD, the level probe pumps that inventory to the accumulator. Liquid is retrieved from the accumulator when the level probe begins to become uncovered. The loop temperature is simply controlled by regulating the pressure and thereby the saturation temperature of the two-phase mixture in the RFMD. By design, the RFMD provides liquid at a nearly constant pressure above saturation, corresponding to few degrees of subcooling.

Cavitating venturiis maintain nearly constant flow to each evaporator over a full range of heat loads. Each load venturi is sized to provide a target exit quality (normally 80%) at each load under full heat load. The flow rate divided by the "choked" flow rate, W/Wnom, is plotted in Figure 2 as a function of the Pressure Ratio, PR. The Pressure Ratio is the ratio of the outlet pressure above saturation to the inlet pressure above saturation. It can be seen that the flow through a cavitating venturi is independent over a wide range of downstream pressures which will vary with heat load. With a constant flow to each evaporator, the outlet quality varies with heat load. Pressure drops in the two phase return lines vary strongly with quality and void fraction, but only weakly with g-field. Therefore, if the two-phase return

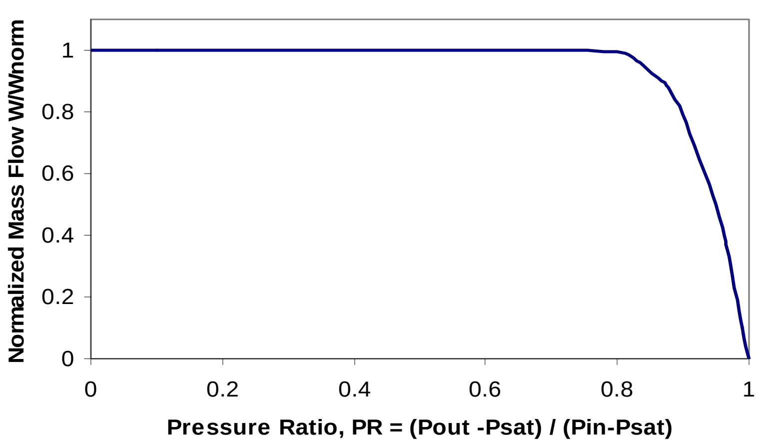

FIGURE 2. Cavitating Venturi Flow Control Characteristics.

lines are sized for the maximum quality and void fraction with a margin of safety, the cavitating venturi will hold the flow constant in all g-fields.

ROTATING FLUID MANAGEMENT DEVICE (RFMD)

A pumping concept was developed and demonstrated for use in a two-phase bus for the space station Freedom that can provide reliable zero-gravity phase separation and liquid pumping. A detailed description of the pump module is described by Banaszynski, et al. (1992). The heart of the system is the Rotary Fluid Management Device (RFMD), which pumps liquid to the evaporator loop and vapor to the condenser to reject heat. Hamilton Sundstrand developed the RFMD to manage two-phase fluid flow in a varying or non-existent g-field. Several Freon® and ammonia designs were extensively tested. A cutaway of a prototype unit and a cross-section drawing of an RFMD are shown in Figures 3 and 4. Testing included zero-gravity Keplerian arc flights on-board a KC-135 and qualification in the thermal-vacuum chamber at NASA Johnson Space Center. Figure 5 shows the zero-gravity KC-135 test loop.

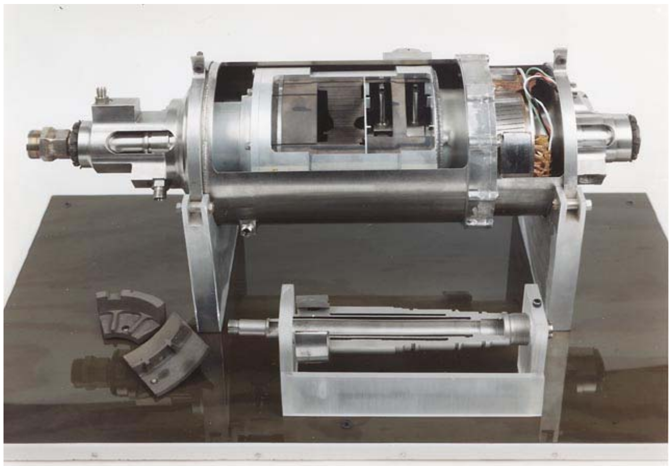

FIGURE 3. Prototype RFMD Cutaway.

The RFMD functions as a pump, a phase separation device, a direct contact heat exchanger and a non-condensable gas vent. The RFMD consists of a two-chamber rotating drum inside a stationary housing where the vapor-liquid mixture is introduced axially into the warm "saturation" chamber. The vapor-liquid mixture is centrifugally separated and the liquid is picked up by the stationary pitot tube using both the liquid dynamic pressure and the hydrostatic pressure developed by the induced g-field. Because the liquid-vapor interface in the drum is at saturation conditions, pressurized fluid at depths below the surface are inherently subcooled (positive NPSH).

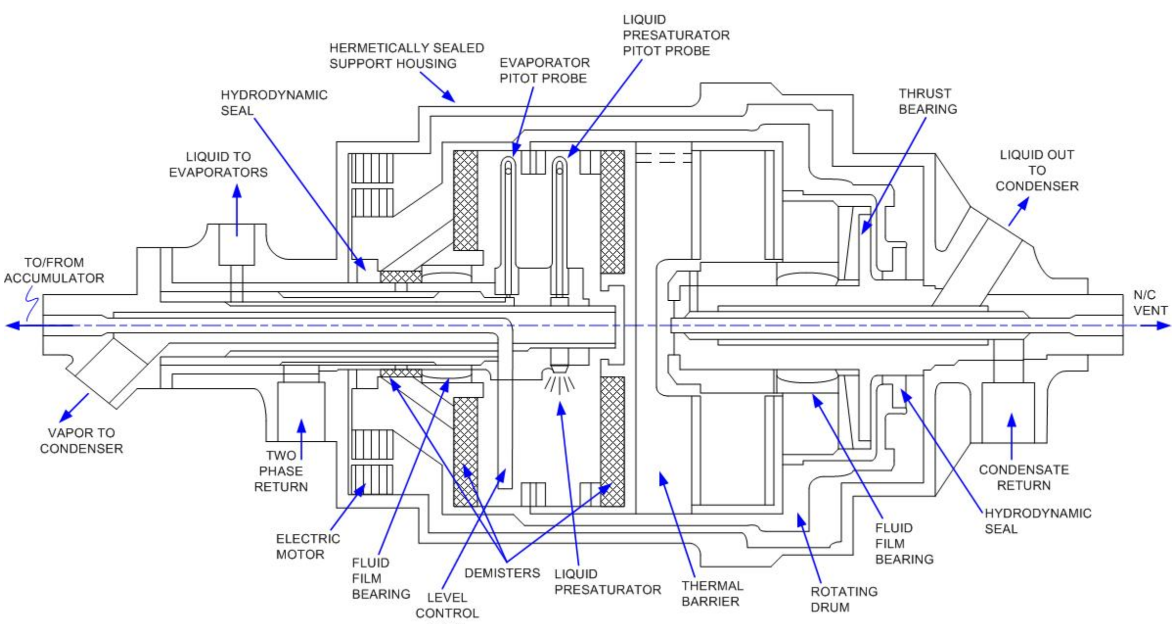

FIGURE 4. Cross-Section of RFMD.

The less dense vapor phase collects in the core where it is extracted to flow to the condenser. The cold chamber pumps the condenser loop by re-pressurizing the condensate. The condensate is pumped back to the warm (saturation) chamber at the outer periphery of the thermal barrier by the centrifugal-hydrostatic head developed by the different liquid levels between the two chambers. The condensate flow is sprayed into the vapor space in the warm chamber where a portion of the wet exhaust from the evaporators is condensed by direct contact.

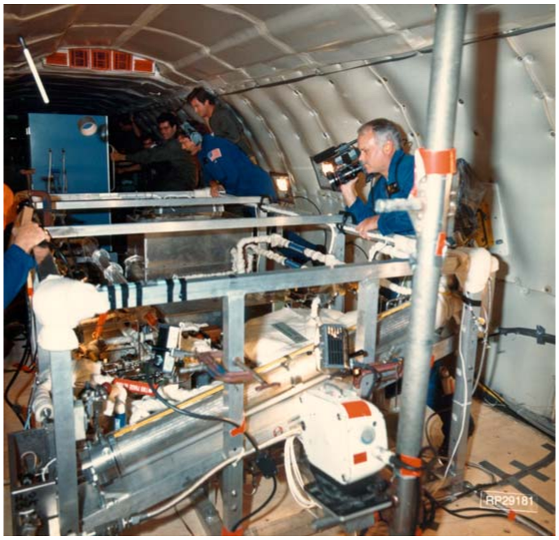

FIGURE 5. KC-135 Flight Test. Clear Shear Flow Condenser in Foreground.

Non-condensable gas, if present, will accumulate in the center of the cold chamber of the RFMD. System operating parameters are monitored to indicate when non-condensable gas has accumulated, and the non-condensable gases are vented. For condenser loop pumping, an insulating wall must be used to minimize heat leak between the cold and warm RFMD chambers. Long life, non-contacting, seal-free (working) fluid film bearings are used for high reliability. Several RFMD models (pre-prototype, prototype, flight test unit, thermal vacuum chamber test unit) have been built and successfully tested with multiple referee fluids and in ammonia.

The RFMD is especially well suited to high heat flux applications with minimal temperature variations. Boiling to dryness is unacceptable in high heat flux applications or when temperature levels need to be precisely controlled. For isothermality and high heat flux conditions the heat transfer surfaces must be completely wetted. The RFMD accepts the returning wet mist from a completely wetted evaporator without compressor slugging or erosion problems that can occur in conventional systems.

HEAT EXCHANGERS

Heat acquisition and heat removal techniques compatible with an active (pumped liquid) system are discussed. Shear flow condensers are compatible with the pumped heat rejection loop and have been designed to operate independent of gravity or orientation. Several evaporator concepts are available to a pumped liquid system, as it is not constrained by capillary limits. Higher velocity heat transfer devices can be employed that are insensitive to gravity and have low thermal resistances. These include swirl flow evaporators, spray systems or compact evaporative laminated coolers.

Swirl Flow Heat Exchangers

Keeping with the fundamental system approach of providing zero-gravity operation by replacing gravity forces with artificially induced forces, the evaporators rely on curvilinear forces developed by the fluid flow. Heat exchangers and cold plates are designed to maintain wet-wall conditions by choosing passage curvatures and fluid velocities that dictate phase separation. A swirl flow heat exchanger can be as simple as a tube formed into either a spiral or a helix. The tube cross-section can be circular, square or rectangular. This is a well-proven phenomenon that has been used to enhance boiling in high heat flux applications. The design and testing of several swirl flow evaporators is descibed Hill, (1985), Niggemann, (1985) and Sorensen, (1984).

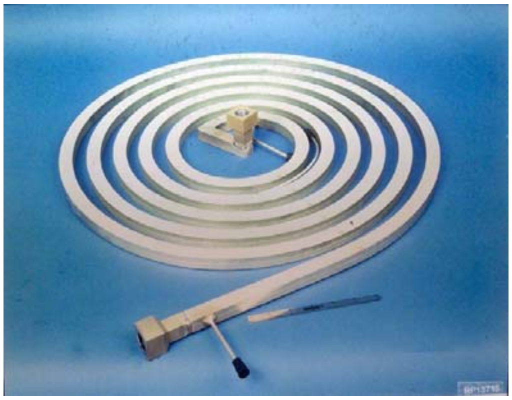

FIGURE 6. Swirl Flow Evaporator.

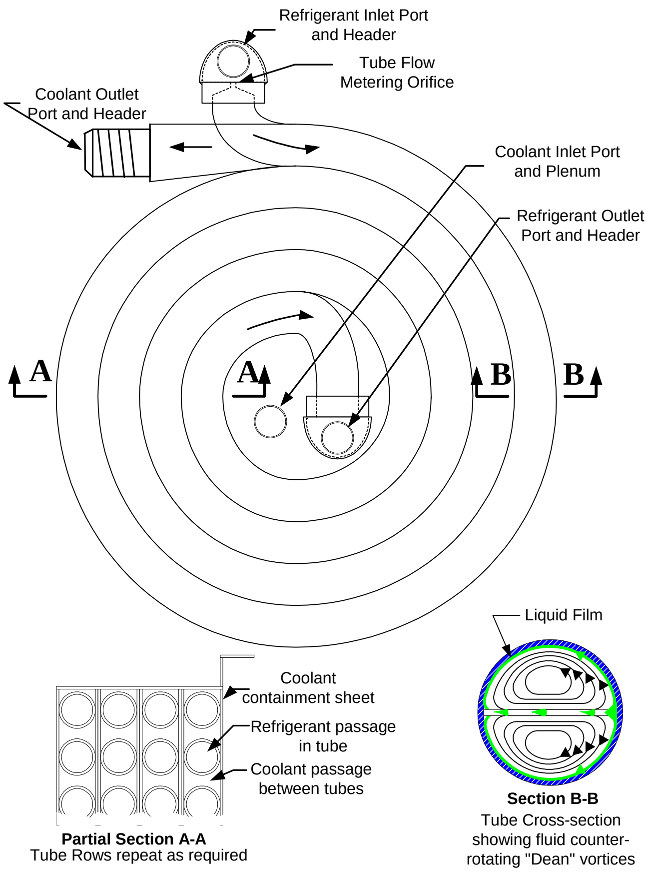

FIGURE 7. Swirl Flow Counterflow Heat Exchanger.

When a two-phase fluid is axially flowing inside the tube, a secondary flow of two counter-rotating "Dean" vortices tend to disperse the liquid fraction on the tube wall with vapor surface velocities greater than the fluid axial velocity. Test data shows enhanced heat transfer coefficients and the liquid film covers the entire tube wall up to very high (90%) quality. The net effect is improved heat transfer with a greatly decreased sensitivity to orientation or g-loading. Wet-wall boiling (nucleate rather than film) to qualities above 90% has been demonstrated, but design practices would be limited to values of 80% or less to maximize heat transfer. Several designs that marry the spiral or helical passages to electronic heat loads and single-phase loops have been developed and tested. A photograph of the swirl flow evaporator tested in zero-gravity and the NASA thermal vacuum chamber in Houston is shown in Figure 6.

The swirl flow evaporator concept can be extended to two-fluid heat exchangers as shown in Figure 7. This design is a counter-flow design with refrigerant flowing from the outside toward the inside and the warmed liquid coolant to be cooled flowing in the opposite direction. The refrigerant first enters a header that distributes the refrigerant evenly between the spiral path tube layers through tube flow-metering orifices at the inlet to each tube. The refrigerant exits the tubes into a collection header at the center of the spiral. The warm coolant enters the heat exchanger at an inlet port on the end plate of the inside of the spiral. From the inlet coolant plenum, the coolant enters the tube layer interstitial spaces and follows the spiral while being cooled by the evaporating refrigerant in the tubes. The heat exchanger consists of the required number of parallel flow tube layers to obtain the necessary heat transfer performance. A thin coolant containment sheet is wound with the tubes to direct the coolant in a spiral counter to the refrigerant flow.

Bonded Laminate Coldplates and Heat Exchangers

Several variations of bonded-laminate heat exchangers have been built and tested that utilize the coolant's latent heat of evaporation in convective heat transfer. Analytical and experimental studies that support the design of laminated evaporators are given in Chang, et al. (1993a, 1993b) and Downing, et al (1999, 2000) and patented by Downing (2001). These units are constructed by diffusion bonding a stack of laminations which have photo-chemically etched flow features. Several versions of an Evaporative Compact High Intensity Cooler (ECHIC) have been built and tested up to 500 W/cm^2 with low thermal resistances, ~0.05 °C/W-cm^2. An increasing flow area along the flow length provides room for the vapor generation reducing pressure drop. The flow passage areas have been designed to limit the change in velocity as the coolant quality increases. The multiplicity of small passages provides extensive surface area that will remain wetted by the turning (tortuousity) of the flow path. A slightly subcooled liquid is fed to the center of each module where it impinges at the center of the module at the heat source surface. Boiling begins as the jet turns to flow in the network of inter-connected fluid passages in the bonded lamination stack. The two-phase flow is primarily in the radial direction in an array of symmetric passages, but it also spreads axially into layers of passages above those that contact the heat source. This flow pattern with the flow area expanding in both the radial and axial directions accommodates the vaporizing flow which is volumetrically expanding. The ability to accommodate the expanding flow and still keep the fluid contained and in intimate contact with high efficiency heat transfer surfaces provides an attractive and unique two-phase cooling approach. For larger heat flux footprints, modular units are ganged together and exhaust into a common header. Figure 8 shows the ECHIC Concept.

In contrast to spray coolers that wet the heat flux surface with a spray of droplets and rely upon the evaporation of the fluid film on the heated surface, the ECHIC cooler has fluid headers (not sprays) that deliver liquid flow for boiling to a matrix of confined passages. The overall heat transfer performance, (ηHA), is the product of the fin efficiency, heat transfer coefficient and the wetted area for a cooler. Excellent performance is achieved because: a) the multi-layer construction of bonded interconnecting channels provides over ten times more wetted surface area than the heat flux footprint, b) the heat transfer coefficients are high because impinging and turning flows keep passages wetted for high convective boiling coefficients, and c) the fin efficiencies are high because the stack has nearly 50% conduction area between the passages and the fin lengths (stack height) are short.

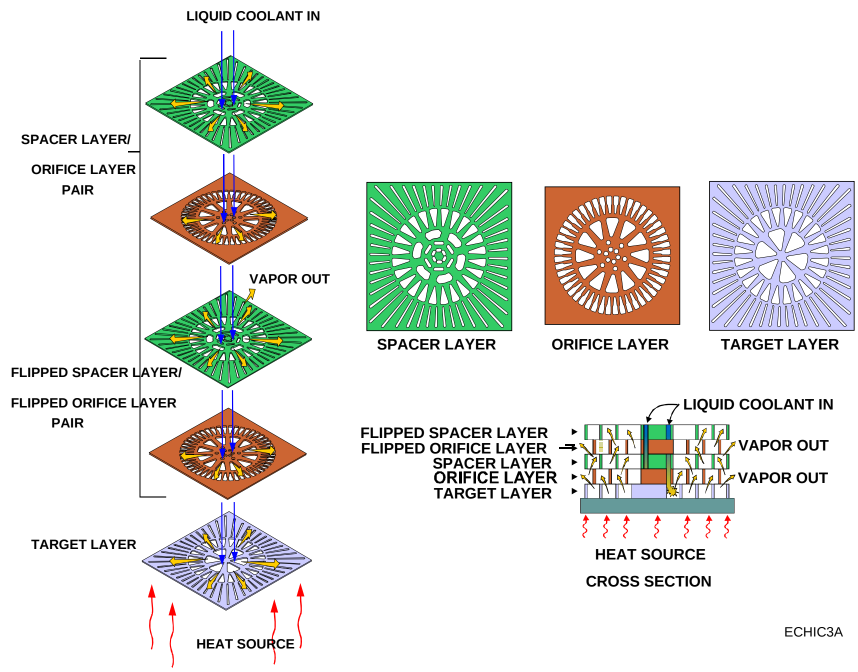

FIGURE 8. Evaporative Compact High Intensity Cooler.

The swirl flow concept has also been applied to an evaporator used to cool a coolant in a compact form factor that is insensitive to g magnitude or direction. This concept is shown in Figure 9. The refrigerant and coolant flow in opposite directions through separate paths in a stack of laminations, thereby matching temperature curves. The coolant path is through a series of jet array orifice and spacer features. The refrigerant path is through a series of parallel flow swirl features. The swirls illustrated in this example are semi-circular with arc connectors between them to approximate a helix.

The pumped loop concept is compatible and necessary to motivate other proven methods of obtaining high heat transfer rates in evaporation at very modest temperature differences, such as spray evaporation. The pressure heads and degree of subcooling needed for spray evaporation can reliably be provided by an RFMD system. Perhaps more importantly, spray systems have significant liquid carry-over that requires phase separation for recirculation of the liquid. A centrifugally-induced phase separation is the most efficient, gravity-independent approach. Capillary forces are orders of magnitude smaller, requiring very large structures and could not handle the required mass fluxes.

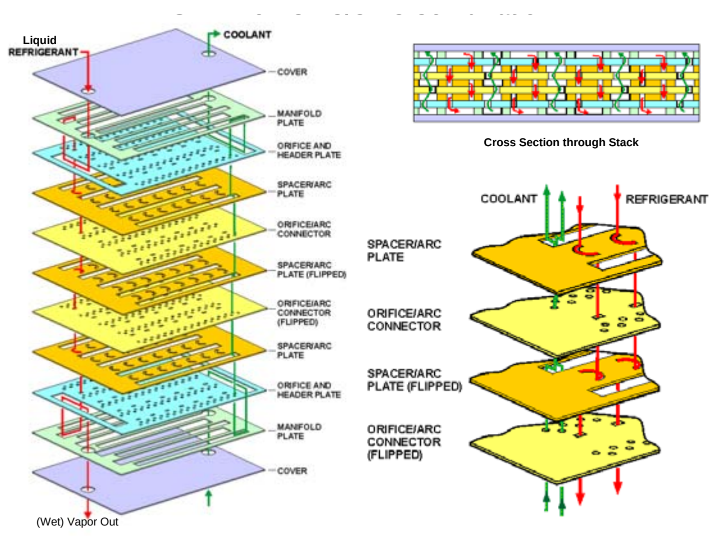

FIGURE 9. Swirl Flow / Compact High Intensity Cooler Heat Exchanger.

Shear Flow Condensers

Shear flow forces are the logical approach for phase-control and stable operation to condensation in zero-gravity. Momentum pressure recovery in a condenser can lead to instabilities, which can result in vapor carryover in isolated channels of a multiple channel condenser. Potential problems with zero-g operation include single channel interface and run-back instabilities, and also parallel path manifold and liquid-leg instabilities. These instabilities can be obviated if the condenser passage cross-sectional area is tapered in the flow direction. Flow instabilities like run-back and liquid-leg are eliminated with the positive pressure gradient exceeding the momentum recovery of condensation. As vapor condenses, velocities are maintained to keep the two-phase flow in a shear controlled regime with a positive pressure gradient. The vapor flow thins the condensate layer, providing phase control and improving the heat transfer by reducing the film thickness. Shear flow condensers have been demonstrated in flat plate designs and in designs using machined channels on the OD of a thick pipe as shown in Figure 10. Both designs showed no evidence of stability issues in up-hill orientations, significantly more adverse than micro-gravity.

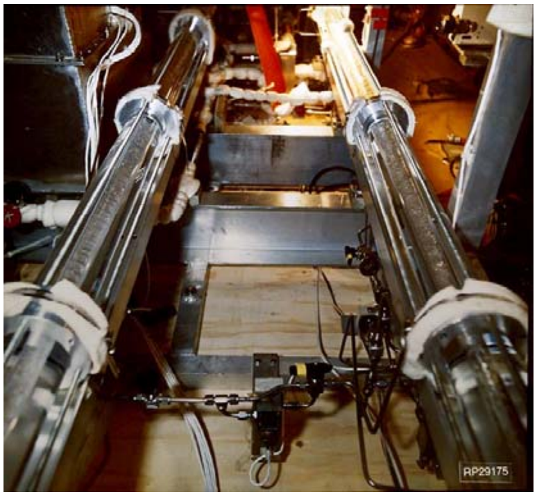

FIGURE 10. Flight Test Shear Flow Condenser.

DEVELOPMENT NEEDS AND PLANS

Although the pumped two-phase thermal management system has been extensively studied and significant testing has been done on loops designed for the space station, more development work is necessary to adapt the system to other platforms. Higher heat fluxes expected on future platforms will require development of high performance evaporators. The radiator to condenser interface is also critical in minimizing the source to sink temperature drops and thereby the radiator requirements. Optimization of the loop parameters (line sizes, pump heads) which drive weight to power trades is unique to each platform. Reducing pump and motor requirements for the RFMD will have a high payback in reducing the penalty to the platform. Also, transport to space (high-g, thermal extremes), start-up and shut-down issues must be addressed. In general, additional development of components is necessary to optimize weight and power while still meeting the thermal transport requirements.

CONCLUSIONS

Increasing thermal power transported over increasing platform size will dictate the use of active two-phase thermal management systems to minimize TMS weight and power penalties. Fluid phase management in a zero or low g environment poses challenges different than on earth. A number of robust and proven concepts can mitigate the lack of gravity and induce phase separation in pumps and within heat exchangers to create an effective active two-phase thermal management system for space applications.

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