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ADVANCED THERMAL CONTROL TECHNOLOGY for COMMERCIAL APPLICATIONS

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ABSTRACT

A number of the technologies previously developed for the thermal control of spacecraft have found their way into commercial applications. Specialized coatings and heat pipes are but two examples. The thermal control of current and future spacecraft is becoming increasingly more demanding, and a variety of new technologies are being developed to meet these needs. Closed two-phase loops are perceived to be the answer to many of the new requirements. This paper discusses all of these technologies and summarizes their spacecraft and current terrestrial applications.

INTRODUCTION/BACKGROUND

The thermal control of spacecraft presents some unique problems not generally encountered in terrestrial applications. Space is a place of great extremes: surfaces exposed to the sun can become quite hot while surfaces facing deep space can become very cold. In addition, any piece of equipment which uses electrical power must reject an equal amount of energy as waste heat. Such rejection of waste heat to the ultimate sink must be by radiation. These factors can create unacceptable temperature extremes for a spacecraft unless some measures are taken to control heat flows. In the past this control was accomplished with special coatings and a unique kind of insulation called multi-layer insulation (MLI). Somewhat later more sophisticated devices such as louvers and heat pipes were developed. These technologies have worked well for applications up to the present which involve a few kilowatts or less and only short transport distances. However, future applications such as the Space Station Freedom, Earth Observing System platforms, and Lunar Base are much more demanding. For these applications a new type of advanced thermal control technology is being developed: closed, two-phase loops which can act as a central thermal bus.

The technologies previously developed for spacecraft thermal control have eventually found their way into certain terrestrial applications. It is reasonable to suppose that the more advanced technologies now being developed will also find commercial and industrial markets. Discussed below are some selected NASA developed thermal control technologies and their spacecraft and commercial applications.

CURRENT THERMAL CONTROL TECHNOLOGIES and APPLICATIONS

Coatings

A variety of special coatings have been developed during the history of space exploration. In general, the purpose of these coatings has been to either reflect or absorb incident solar radiation, or to radiate or prevent the radiation of waste heat. These functions are characterized by the surface "absorbtivity" and "emissivity", respectively, of a material. For a given surface, the ratio of these two parameters combined with the radiation impinging upon it and the heat conducted to/from it will determine the net flow of energy into and out of this surface. All surfaces taken together will determine the net thermal balance of the spacecraft. Thus, by selecting the emissivity and absorbtivity of the exterior surfaces the flow of energy into and out of a spacecraft can affected. For early spacecraft, which were small and of low power, such coatings combined with MLI were generally enough to provide adequate thermal control.

The special coatings developed for space applications have found a number of commercial applications. For example, the technology used for coating astronaut helmet visors is now used for window coatings on buildings. In addition, silicate paints, similar to those developed for spacecraft, were used during the recent renovation of the Statue of Liberty. The aluminum oxide coatings used to protect many silver polishes from tarnishing are similar to those developed by NASA. Also, conductive coatings such as indium oxide and indium antimonide are employed to coat liquid crystals.

Heat Pipes

Heat pipes are inherently very simple devices. They are used to conduct heat over relatively long distances with only a small temperature drop. In its conventional form, the heat pipe is a closed tube or chamber whose inner surfaces are lined with some sort of porous wick. In operation the wick is saturated with a the liquid phase of the working fluid while the remaining space is saturated with the vapor. Heat is applied to the evaporator end of the pipe. This heat is absorbed by the liquid which then vaporizes. The lost liquid in the wick is replaced via capillary forces in the wick. The resulting pressure difference between the vapor and liquid phases drives vapor from the evaporator end and to the condensing end, where it condenses back into a liquid and is absorbed by the wick. Capillary forces in the wick pump the liquid back to the evaporator area. Hence, a closed heat transport loop is created. This process is depicted in Figure 1. since the process makes use of the fluid's latent heat of vaporization a significant amount of heat can be transported relative to fluid flow rate and unit size. The process can continue indefinitely as long as the fluid flow passage is not blocked and a sufficient capillary head can be maintained. There are no moving parts to wear out.

Heat pipe technology was originally developed in the early 1960's. They have since been extensively used for spacecraft thermal management. A wide variety of heat pipe designs have been developed over the years to meet different thermal control needs. However, almost all of these designs were for moderate temperature applications (e.g., near room temperature) and employed ammonia as the working fluid. Due to basic thermophysics a given heat pipe design will be applicable only for a limited temperature range. Ammonia, which has both a very high latent heat of vaporization and a high surface tension (which is needed for good wicking) is an outstanding fluid for moderate temperature applications from about minus 40 degrees Celsius to about plus 50 degrees Celsius. Although a few experimental heat pipes for cryogenic applications have been fabricated, these are not yet generally available for commercial or spacecraft applications. High temperature heat pipes have, however, been fabricated and are now commercially available. These pipes employ a liquid metal as the working fluid.

Heat pipes normally operate as high efficiency heat transfer devices with a fixed conductance. However, by modifying their design slightly it is possible have them operate with a conductance that is variable in response to some external driver function. It is also possible to design a heat pipe so that it operates as a diode and conducts heat only in one direction.

Although deceptively simple in concept, development of a properly operating heat pipe requires careful consideration to numerous design details and the cleaning and charging procedures. Special procedures must also be employed in testing. References 1 and 2 provide a good summary of the basic issues involved in heat pipe design.

Heat pipes have found their way into a wide variety of commercial applications. Virtually all commercial communication satellites depend upon heat pipes for thermal control. There are also a large number of terrestrial applications. For example, elements of the technology were used for thermal control of the perma-frost for the Alaskan pipeline (over 125,000 pipes were used). In addition, heat pipes have been used in many industrial waste heat recovery systems. Many high temperature furnaces use heat pipes to provide extremely isothermal conditions (less than 1 degree Celsius) . Heat pipes are also used to remove heat from industrial and medical (e.g., dental) drill bits. A major application is for cooling high power electronic equipment, especially in military aircraft.

The primary limitation to the use of heat pipes in terrestrial applications is generally not power or transport length. Rather it is typically the maximum elevation that can be tolerated between the evaporator and the condenser ends. Generally, the evaporator can be no more than a few inches above the condenser or the wick cannot pump and the heat pipe will fail. However, if the condenser can be on top then the pipe can be operated in a "reflux" mode and large height differentials are possible.

Two-Phase Pumped Loops

Future planned space structures, such as the Earth observing System platforms and Space Station Freedom, will pose a much more demanding thermal control problem than current spacecraft. They will have power levels in the tens of kilowatts, transport distances in the hundreds of feet, numerous heat load sources dispersed throughout the structure, and will require tight temperature control (+/- 2 or 3 degrees Celsius). In addition, the numerous heat load sources will all require this cooling under a variable load schedule. These requirements virtually prohibit the use of conventional passive or single phase thermal control technology.

Pumped, two-phase thermal control technology has been developed to meet the emerging requirements discussed above. This technology is essentially a major evolutionary step beyond heat pipes and offers about a two order magnitude improvement. In a two-phase loop, a subcooled liquid refrigerant (ammonia is the preferred fluid) is first introduced into an evaporator, which typically has some sort of wick structure to promote fluid distribution. Heat from the equipment to be cooled is applied to the evaporator where it is absorbed by vaporization of the liquid. It is important to note that the equipment to be cooled sees an isothermal sink. The refrigerant then leaves the evaporator as either a saturated vapor or two-phase fluid. It then travels through a tube to a condenser where it gives off heat and returns to a liquid state. This condenser may be either a radiator or a heat exchanger connected to some intermediate sink. The process is depicted in Figure 2. References 3 and 4 provide a brief technical overview of the technology.

Three basic types of closed, two-phase loops have been developed. These are characterized primarily by the type of motive force used to circulate the fluid through the loop. In a Capillary Pumped Loop (CPL) the liquid,is circulated by only the wicking forces generated within the evaporator's wick. Figure 3 depicts such a process. This is similar to a heat pipe, except that in a CPL the liquid and vapor phases are separated and flow through different lines. The effluent from such capillary evaporators is typically a saturated vapor. Outstanding characteristics of this system type include the fact that the capillary based evaporators are self regulating (i.e., the more power applied, the more they pump, up to their limit). In addition' there are no moving parts to wear out. A potential limitation is the relatively small pressure head generated (half of a psi is typical). CPL's have demonstrated a two order of magnitude improvement in heat transport capability (power times distance) over heat pipes.

The second major type of two-phase loop involves the use of a small mechanical pump to supply refrigerant to the evaporators. In this type of system, depending on the system design the evaporator may discharge either a pure vapor or a vapor/liquid mixture. The evaporators, however, do not provide any pumping action of their own. In either case the effluent goes to a condenser (heat exchanger or radiator) and is condensed back into a liquid. It is then pumped back to the evaporator and the cycle continues.

In the third major system type, a mechanical pump is used in concert with capillary evaporators. This combines many of the advantages of the capillary and mechanically pumped systems; the capillary pumps are self regulating and the mechanical pump provides additional pressure head to drive the fluid through the loop. This system concept is depicted in Figure 4. Variations on these basic system concepts are also possible.

Two-phase thermal control technology has been baselined for both the Earth Observing System platforms and Space Station Freedom. These large space facilities will require the high power capacity, long transport capability, low relative weight, and isothermality offered by two-phase technology. It is anticipated that any future large space facility with similar requirements would also need to make use of this technology.

To date there are no known commercial applications of the two-phase thermal control technology discussed above. Ammonia refrigeration systems have been operated in industrial and commercial applications for many years, but these have involved the generation of a temperature differential for refrigeration purposes. The technology discussed above is concerned with the efficient transfer of heat over relatively long distances, not refrigeration. However, just as heat pipes have proved useful for commercial applications it would appear that two-phase loops could solve some terrestrial heat transfer problems. The use of a mechanical pump might eliminate the height restriction problems existent with heat pipes.

FUTURE THERMAL TECHNOLOGY

The technology discussed above will be able to provide thermal control for the NASA missions scheduled to date. However, several additional technologies will be required to enable or significantly enhance future proposed space activities. For example, in order to provide thermal control for a Lunar Base a new type of heat rejection or thermal storage technology will be required. Heat pumps have been proposed to solve this problem. Although heat pumps have been used for years in terrestrial applications some modifications will be required for space applications. As these modifications will likely address reliability and efficiency some technology transfer back to the commercial sector seems reasonable. Other new thermal control technologies needing development for space applications include low temperature heat pipes and thermal storage devices. If the past is any guide then these technologies will also offer terrestrial applications.

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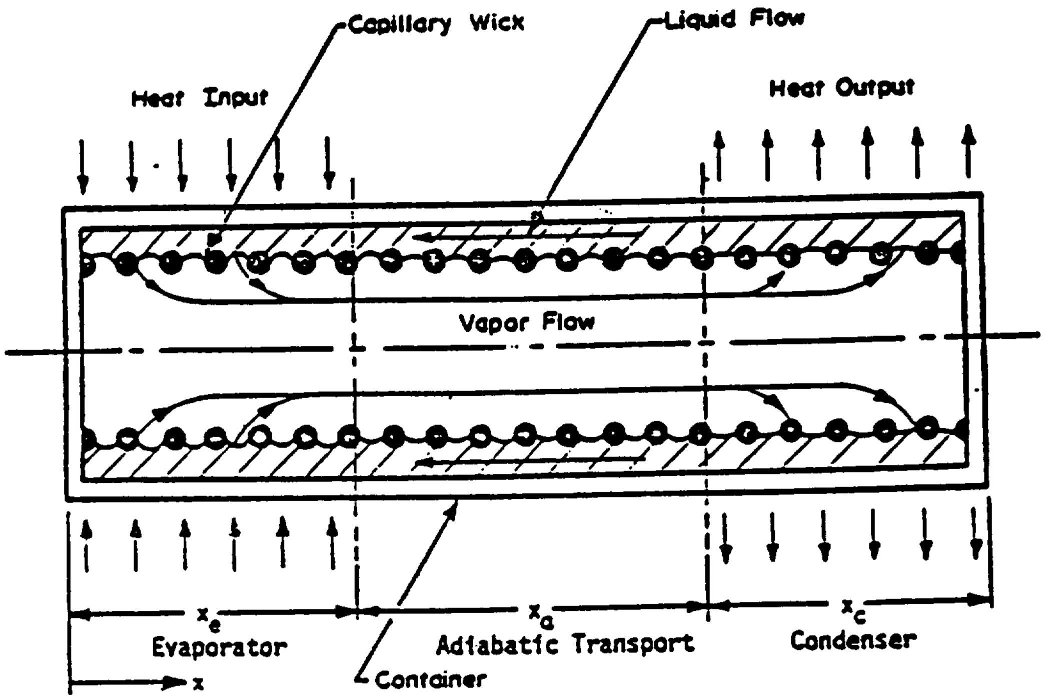

FIGURE 1. **Components and Principle of Operation of a Heat Pipe**

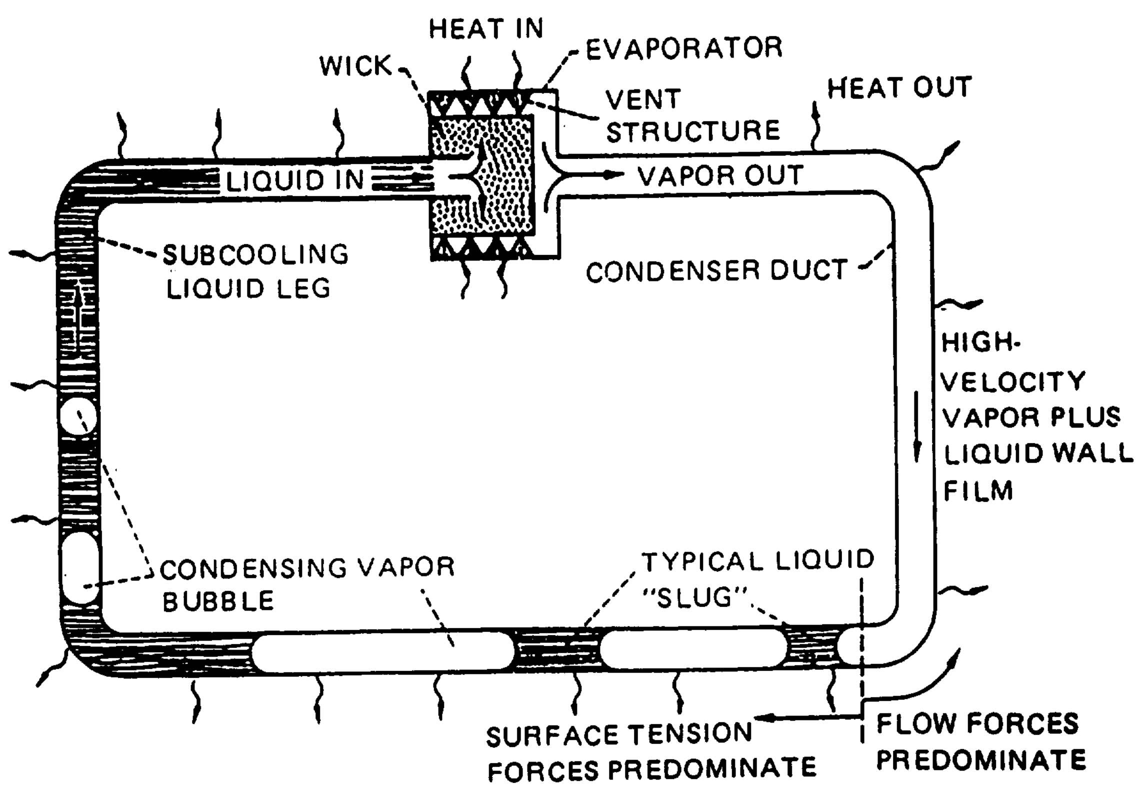

FIGURE 2. **Principle of Operation of a Closed, Two-Phase Loop**

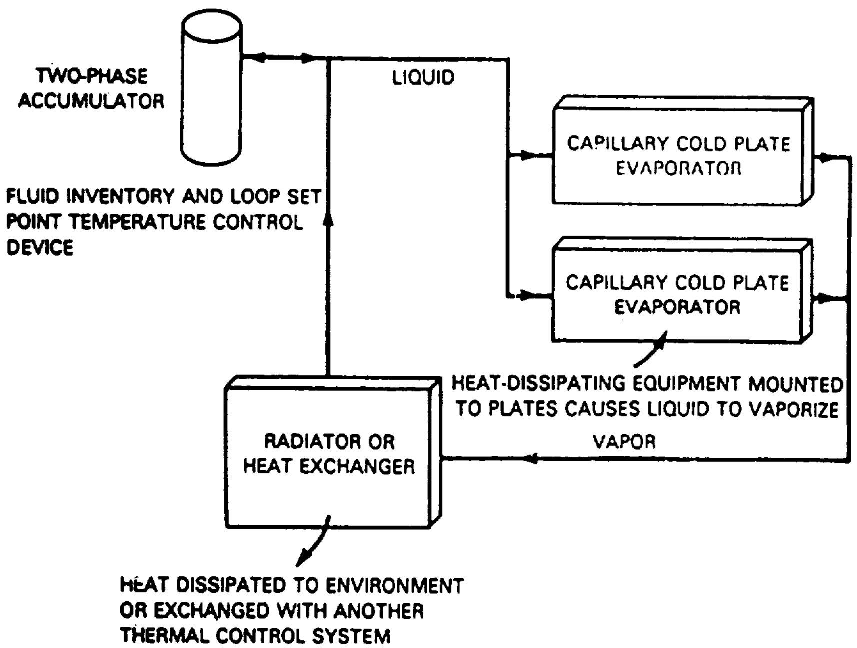

FIGURE 3. **Capillary Pumped Loop**

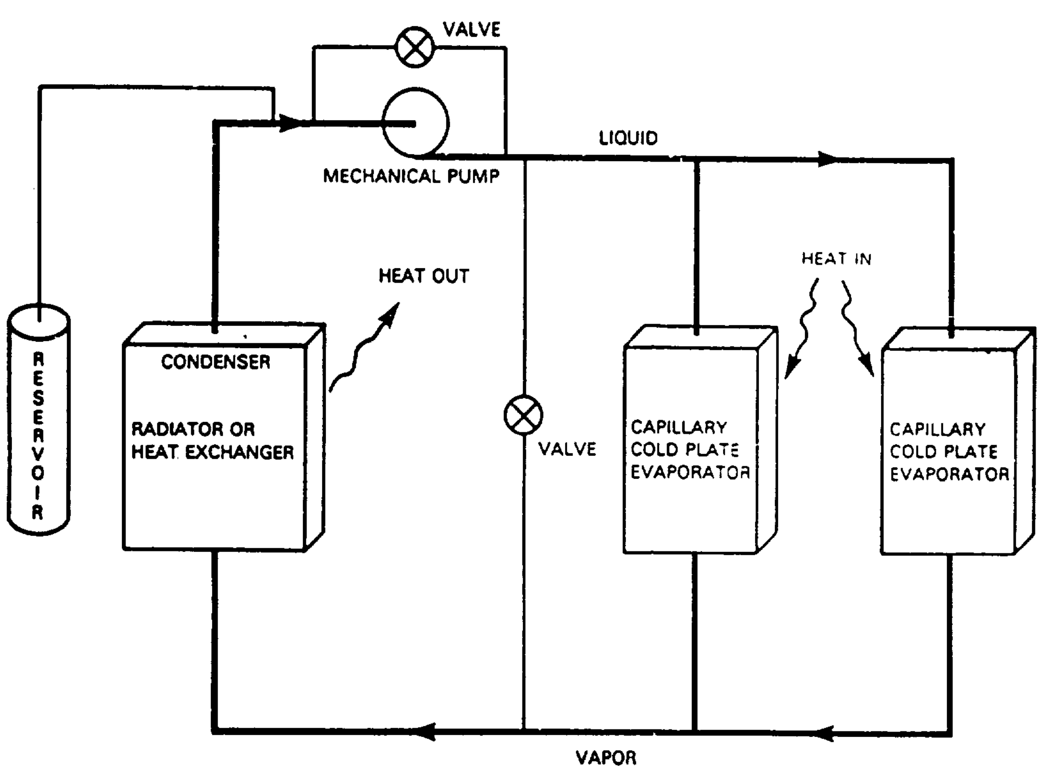

FIGURE 4. **Capillary/Mechanically Pumped Loop (Hybrid)**