STUDY OF SPACE COOLING SYSTEM CONSISTING OF ALUMINIUM AMMONIA HEAT PIPE AND VARIABLE EMITTANCE MEMS RADIATOR

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Abstract—*Micro-Satellites such as the Magion 4,5 and Large manned spacecraft like International space station(ISS) use axially grooved u-shaped aluminum heat pipes with ammonia as the working fluid expected to be integrated with newly emerged variable emittance radiators to accomplish active thermal control with high precision. However, these integrated space cooling systems require well-designed control policies that demand a good understanding of its dynamic open loop performances. Control action is produced through the Proportional-Integral-Differential controller (PID) to improve system adaptability and robustness and for easier practical implementation. A PID controller for heat flux errors and a PID controller for temperature regulation errors as inputs are adaptively adjusted by a fuzzy logic of control. This control action is coupled with a variable emittance micro-electro-mechanical-system(MEMS)radiator. Cooling behavior is dominated by radiation of heat due to the absence of air and depends on the degree of exposure. This dynamic model can be used to calculate mass flow rate and condensing pressure of the working medium directly through system nodal temperatures and is hence apt for control engineering applications. The closed-loop transient performance of fuzzy control scheme has been studied and results conclude that the hypothesized control scheme improves thermal control effects and ensures safe operation of heat pipe space cooling systems*.

Keywords—heat pipes, variable emittance, fuzzylogic,micro-electro-mechanical-system, nodal temperatures.

I. INTRODUCTION

The function of a Space Cooling System or specifically a Spacecraft Cooling System (SCS) is to maintain component systems within acceptable limits during all phases of a mission. It must adjust to the varying environment such as deep space or solar/planetary flux and has to eject the internal heat generated by the spacecraft operations. Thermal control is necessary to ensure optimum performance because if operating temperatures exceed the acceptable limits, then the component could be damaged or it could lead to poor performance. The Spacecraft cooling systems work in two ways:

- Controls overheating either by thermal insulation from external heat fluxes or by proper heat removal from internal heat sources.
- Protects components from too cold temperatures either by enhanced heat absorption from external sources or by heat release from internal sources.

II. LITERATURE REVIEW

Kai Zhu et al., in their journal article on Dynamic performance of loop heat pipes for cooling of electronics [1] explain that heat pipes, which have numerous advantages such as high heat transfer coefficient, non-movable components, longer transport distance, and compact structures, emerges to be one competitive option for electronics cooling. Based on the node analysis method and the conservation of energy and mass it develops a mathematic model to simulate the operation of heat pipes. Results show that the operation temperature of evaporator ranges from 47.5°C to73.1°C, which implies that the heat pipe can effectively cool down the CPU at different running status.

Shengzhu CAO et al., spread light on the Variable Emissivity Surfaces [2] and possible solutions to actively vary the heat rejection of the satellite in response to variations in the thermal load and environmental condition, such as thermochromic, electrochromic, micro louvers and thermal switches, etc. Micro louvers with small volume, low weight,less power consumption and large emissivity variation, will be the most suitable solution. The design and actuation of these louvers are also described.

Valeri V. Vlassov et al. presents a New Concept of Space Radiator with Variable Emittance [3] in which the radiator is composed of two stages which exchange heat through radiation between finned surfaces covered with variable emittance coatings, whose emissivity is increased with temperature. Under cold conditions the radiative heat coupling between the stages is minimal, preventing the equipment subcooling, while in hot conditions the heat exchange is increased. Design optimization procedure is carried out considering two optimization criteria: minimization of the radiator mass and the power consumption of heater under cold conditions. It is envisioned that the utilization of such radiators in micro-satellites will lead to considerable electric power savings for safe heaters and may contribute to a longer satellite life. In the design trade-off, the cost for this saving is additional radiator mass and volume.

Fuzzy incremental control algorithm [4] reviewed by Su-Jun Dong et al., proposes it for control of an LHP space cooling system comprising a loop heat pipe and a variable emittance radiator with MEMS louver. The generating and performing algorithm of the fuzzy control rules is provided with an analytical formula based on the understanding of dynamics and control mechanisms of the space cooling system. Numerical simulation results on the closed loop control effects suggest that the proposed control strategy takes advantage of no steady error, small overshoots and short settling times; thus, benefiting safe, highly accurate and reliable operation of the entire space cooling system.

LI Yunzea et al., hypothesis a Dual-driven Intelligent Combination Control [5] of the heat pipe space cooling system to improve the temperate control and heat flux tracking effects. Both temperature regulation and heat flux tracking errors are employed to generate the final control action; their contributions are adaptively adjusted by a fuzzy fusing policy of control actions. The closed-loop transient performance of the control scheme is numerically investigated. The results conclude that the proposed intelligent combination control scheme not only improves the thermal control effects but also benefits the safe operation of HP-SCS.

III. TECHNICAL ASPECTS

a. Working Principle

With the invention of electronic devices, effective thermal management becomes necessary in order to control fast increasing heat from the Central Processing Units (CPU). Loop heat pipes (LHP), consisting of an evaporator, a condenser, a compensation chamber, a vapor transport line and a liquid transport line, receive more attention. Due to numerous advantages such as high heat

Transfer coefficient, non-movable components, longer transport distance, and compact structures, LHPs demonstrate a big potential of being used for electronics cooling.

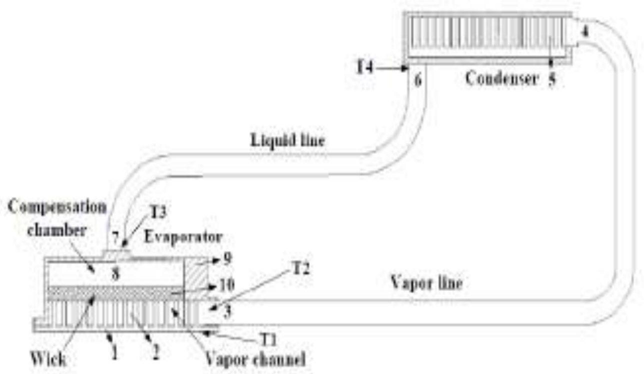

Fig.1: Schematic of Loop Heat Pipe System

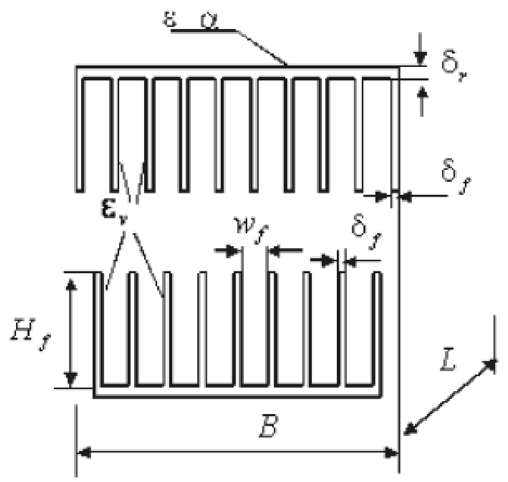

Fig.2: Variable Emittance Space Radiator

The evaporator is the core component of LHP, which provides sufficient capillary force for the cycle of the working fluid. Ammonia is selected as the working fluid due to the lower boiling point. In the evaporator, the copper foam is chosen as a wick. The vapor channel arrays with a high depth-to-width ratio are fabricated on the basement of the evaporator.

These Loop Heat Pipes were originally connected to large radiators with bulky Thermostat controlled louvers and power-hungry heaters. Satellites with short design cycles and fewer resources, volume, and surface, require an active approach. Commonly used active methods such as electric heaters, heat pipes or mechanical louvers incur additional electric power requirements, weight, and bulkiness to the system. New, more flexible approaches are desired to address these issues. One solution is using micro louvers to actively adjust the exposed area of high emissivity radiator to space. The micro louver‛s small size and low weight mean they can be attached to the radiator as a variable emissivity surface and do not add substantial weight or bulk to the spacecraft.

In order to avoid the problem with the high absorptivity of the variable emissivity coating, a new concept for a space radiator was proposed called VESPAR (Variable Emittance Space Radiator), which takes the advantage of the variable emissivity, while keeping a low absorptivity for the entire assembly. The VESPAR is composed of two stages having internal extended fin surfaces for improving radiative heat transfer between them.

B = Width, m
L = Length, m
δ = Thickness, m
ε = Emissivity
H = Height of radiator fins, m
w = Distance between fins of each plate, m
α = Solar absorptivity

With such a two-stage concept, the intrinsic high solar absorptivity of the variable emittance coating is not an issue anymore: The Sun heat flux does not enter the interior of the radiator, and the external surface of the upper stage is covered with a conventional solar reflector coating, with low absorptivity. Moreover, with the use of VESPAR, there is an increase in the area available to radiate heat to space. In the HC, this increases the ability of the radiator to reject heat to space.

LHP and variable emittance radiators like MEMS louver together can realize the high accurate active thermal control tasks by adjusting the heat radiation process at the outer surface of a space radiator. However, this depends on a thorough understanding of the system dynamics and the considerate design of the active control schemes. A concise dynamic model and a practical control policy are required for the successful control of LHP space cooling systems.

As the exhaust heat is applied to the evaporator, it is transferred by conduction through the evaporator structure (Fig. 3) to vaporize the liquid inside. The vapor generated by the input heat travels along the vapor line to the condenser where heat is rejected to outer space by the variable emittance radiator and the vapor is condensed. The condensate enters the liquid line and is pumped back to the evaporator by the primary wick inside the evaporator which acts as a capillary pump and provides the major pressure head for the flowing working fluid. There is a small compensation chamber referred here as a reservoir inside the evaporator and a secondary wick provides the capillary path for fluid communication between the main part and the reservoir.

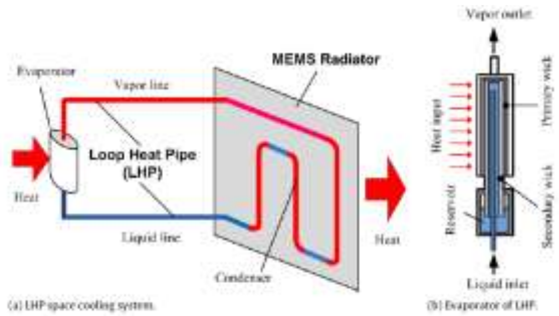

Fig.3: Loop Heat Pipe coupled with MEMS radiator

Fig. 4 illustrates the scheme of the variable emittance radiator. A MEMS louver array is mounted on the high emittance radiator surface to control the leaving heat flux. The cooling behavior of the radiator is dominated by the heat radiation between the spacecraft and it's orbit environment since there is no air outside. When a louver cell in the MEMS array is opened, the high emittance radiator surface under it is exposed to the space environment; otherwise, the low emittance surface of the cover cell will face space. Therefore, by controlling the number of open louver cells in the MEMS array, the whole cooling ability of the space cooling network can by be adjusted with ease. We define the exposing degree ϕ_r as the radiator surface ratio between the exposed area under the opened louver cells and the total area of radiator surface. The radiation heat flux leaving the radiator is governed approximately by

$Q_r = \varepsilon_e \zeta A T_r^4 = [(\varepsilon_h - \varepsilon_l)\Phi_r + \varepsilon_l]\zeta A T_r^4$ (1)

where ζ is the Stefan–Boltzmann constant; A and T_r are total area and an average temperature of the radiator surface; ε_e is the equivalent emittance of the radiator which can be determined by the emittance of the high emittance radiator surface (ε_h) and that of the MEMS louver cells (ε_l).

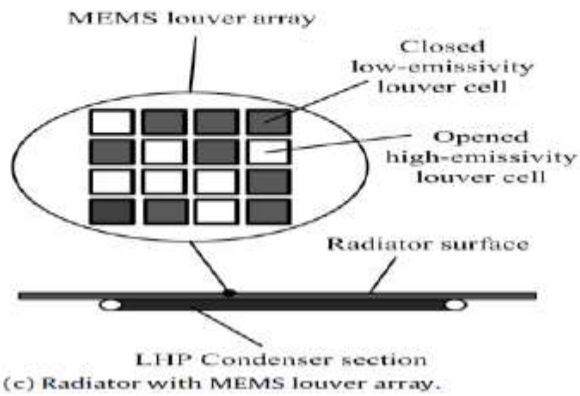

Fig.4: Radiator with MEMS Louver array

b. Control Policy

The fuzzy logic methods which were proved to be valid in the fields of spacecraft altitude control, signal integration, and adaptive tracking control, were also reported as effective in resolving temperature control issues emerging in hydraulic heating, thermoelectric cooling, and energy conversion processes. This reported fuzzy logic employed controllers include the fuzzy control scheme for the hydraulic heating process, the fuzzy coordinate control of TEC and its forced cooling fan in the Nano-satellite space simulator.

The block diagrams of the controlled LHP–SCS and its fuzzy incremental controller (FIC) are illustrated in Fig. 5(a) and (b) respectively. The temperature of the cooled object is measured and compared with its reference value, then the tracking error is fed to the FIC, as shown in Fig. 5(a). The FIC outputs the controlling variable which manipulates the exposing degree of the variable emittance radiator with the MEMS louver. As shown in Fig.5(b), the major parts of the FIC comprise a fuzzifier, an inference engine, a defuzzifier and a fuzzy rule base. Two auxiliary numerical operators are used for the real-time differential and integral calculations of the error increment delta en and current controlling variable ϕr respectively. The control error en and its increment delta en are normalized by the factors Ke and Kc and then enter the fuzzifier; the produced linguistic values (E, CE) are compared with the fuzzy rules in the fuzzy rule base by the fuzzy interference engine.

A nine-element fuzzy set system {NG, NL, NM, NS, ZE, PS, PM, PL, PG} in Table 1 is used to characterize the linguistic values of en, delta en and delta un. Each fuzzy set (or its linguistic value) is associated with a crisp number as an analytical rank for the convenient performance of the control rules

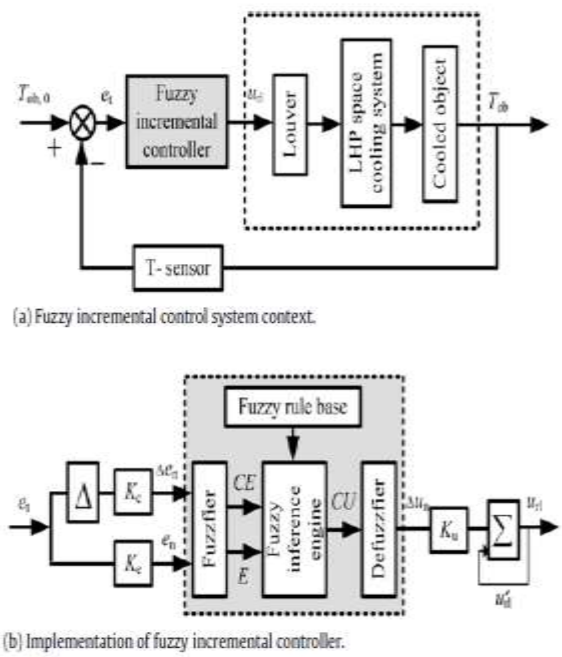

Fig.5: Fuzzy Incremental System Context and Controller Implementation

Theoretical analysis and simulation study of the LHP space cooling system dynamics suggest that a suitable control action for different control situations should be in accord with the following fundamentals:

A positive en usually requires a negative controlling variable increment when delta en is very small, and a negative en often requires a positive one under the same situation.

A large en needs a large controlling variable increment while a small delta un is suitable for small en, whether en is positive or negative.

Fuzzy sets and their linguistic value.

Fuzzy sets	Ranks	Linguistic values
NG	−4	Negative great
NL	−3	Negative large
NM	−2	Negative medium
NS	−1	Negative small
ZE	0	Zero
PG	4	Positive great
PL	3	Positive large
PM	2	Positive medium
PS	1	Positive small

Table1: Fuzzy Set System

A positive delta en will strengthen the requirement for a negative controlling variable increment when en is positive and alleviate the positive controlling variable increment value when en is negative.

Similarly, a negative delta en will strengthen the positive incremental trend of the controlling variable when en is negative and alleviate the negative intention of the controlling variable increment when en is positive.

When the absolute value of en is small, the impact of the control error change delta en should be large, otherwise, the impact should be small.

On the basis of these control knowledge insights, a rank-based generating and performing an algorithm for the fuzzy rules is derived in

$\ell (i, j) = -1 \times nInt(\omega i \times i + (1 - \omega i) \times j)$ (2)

where ωi is the error impact power determined by the rank of the input error (ωi = 0.4 for i = 0, 1, ωi = 0.5 for i = 2 and ωi = 0.6 for i = 3, 4); the return value of the function nInt (x) is the nearest integer number of the input x.

This proposed FIC not only improves the temperature control and heat flux tracking effect obviously but also promises a more stable thermal and hydraulic conditions for the safe operating of the LHP structures and working fluid.

IV. CONCLUSION

Using recently developed temperature dependent variable emissivity coating and an innovative geometry MEMS Radiator has no moving parts being in principle more reliable than the conventional thermal louvers. Based on the suggested model, the dynamic performance of LHP under the assumed running status of CPU can be investigated. The highest and lowest operation temperatures of the evaporator can be maintained in the safe operating temperature range. Use of Aluminum instead of conventional copper heat pipes leads to a reduction in weight indirectly aiding energy conservation. The numerical analysis on the control effects suggests that the overshoots and settling times of the controlled variable and the operating state parameters of the controlled LHP space cooling system have been obviously reduced under the proposed FIC scheme compared with the traditional PID approach.

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BIOGRAPHIES

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