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HEAT PIPE COOLING SYSTEM WITH SENSIBLE HEAT SINK*

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INTRODUCTION

During hypersonic flight, the aerodynamic heat flux at uncooled stagnation regions can produce temperatures beyond the operational capability of virtually all structural materials. In such instances, the use of ablative materials may limit the temperature rise to acceptable levels. However, ablation can produce undesirable changes in the size and shape of affected stagnation regions.

If there is a suitable heat sink available, an alternate thermal protection approach is to utilize a heat pipe cooling system to transport heat from regions of high aerodynamic heating to the heat sink for ultimate disposal. The heat pipe approach is attractive because, in contrast to pumped cooling loops, heat transport is virtually isothermal and separate pumps and power supplies are not required.

Earlier studies have indicated the feasibility of heat pipe cooling for the leading edges of hypersonic aircraft wings (refs. 1,2,3). With this concept, a radiation heat sink is employed on the upper wing surface, where the aerodynamic heating rate is relatively low. A continuous heat pipe structure extends around the wing surface, from the regions of high aerodynamic heating to the radiation heat sink on the upper surface. Aerodynamic heat incident on the leading edge is then transported through the heat pipe structure to the upper surface, and dissipated by radiation to the environment.

This paper deals with a heat pipe cooling system which employs a sensible heat sink. With this type of system, incident aerodynamic heat is transported via a heat pipe from the stagnation region to the heat sink, and absorbed by raising the temperature of the heat sink material. The use of a sensible heat sink can be advantageous for situations where the total mission heat load is limited, as during re-entry, and a suitable radiation heat sink is not available.

BASIC CONCEPT

The basic principle involved is illustrated in figure 1 for nose tip cooling. A cylindrical heat pipe occupies the central region of the nose cone. The hemispherical forward end of the heat pipe protrudes into the air stream, and serves as the nose tip. The heat pipe is surrounded by an appropriate heat

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sink, which in turn is surrounded by ablative or temperature-resistant material. An optional heat shield limits heat transfer between the heat sink and the outer layer.

Aerodynamic heat incident on the nose tip is transported through the heat pipe and deposited in the adjacent heat sink. The cooling system thermal capacity is sufficient to absorb the total mission heat load on the nose tip, while limiting peak temperatures to levels consistent with the operational temperature capability of the heat pipe and heat sink materials. Heat incident on the lateral nose cone surface is generally of a much lower intensity than that experienced over the nose tip, and can be dissipated through the conventional ablative process or through sensible heating of a temperature-resistant layer.

With this cooling system, temperatures can be limited to levels permitting a metallic nose tip of fixed size and shape, even under exposure to stagnation heat fluxes on the order of thousands of w/cm^2.

DESIGN CONSIDERATIONS

A preliminary investigation of a heat pipe nose tip cooling system of the type described has been carried out for a re-entry vehicle (ref. 4).

COOLING SYSTEM GEOMETRY

The geometry of the heat pipe cooling system is shown in figure 2. In general, the axial cooled length X_a must exceed the nose radius R_n in order to maintain a nonzero ablator thickness between the cone surface and the heat sink. The heat sink may be mounted outside the heat pipe in a conical configuration, as shown in figures 1 and 2, in a cylindrical configuration, or as a combination of the two. Alternatively, the heat sink may be located inside the heat pipe by thickening the wick by an appropriate amount.

The conical heat sink configuration makes more effective use of the available volume within the nose cone than the cylindrical or internal configurations. The overall length required to accommodate the heat pipe cooling system can then be minimized.

To further reduce the heat load and hence cooling system size and weight, the heat pipe radius R_c at the start of the heat sink section can be made smaller than the nose radius R_n. The axial cooled length X_a is then smaller than if R_c were equal to R_n.

MATERIALS

Since sensible heat is the heat absorbing mechanism, the cooling system should be characterized by a high thermal capacity (i.e., heat absorption capability) per unit weight and volume. This requirement leads to the selection of heat pipe and heat sink materials with high mass and volumetric specific heats, and with high operational temperature capability. In addition, the heat pipe envelope should have high thermal conductivity to minimize the temperature grad-

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ient and thermal stress in the stagnation region, as well as good strength at anticipated operating temperatures. Finally, the various heat pipe and heat sink materials must be chemically compatible.

For the application under consideration, lithium was selected as the heat pipe fluid and as the primary heat sink material. TZM molybdenum was selected as the heat pipe containment and wick material, and for containment of the lithium heat sink liquid. These materials satisfy cooling system operational requirements quite well. Additionally, lithium has the highest heat transport capability of the various heat pipe fluids, and its operational temperature range is quite compatible with thermal capacity requirements.

OPERATING TEMPERATURE

As previously stated, the highest feasible operating temperature is advisable for the heat pipe cooling system, in order to minimize system volume and weight. TZM is compatible with lithium to at least 1920°K (3000°F), and is probably adequate from the strength standpoint to at least 1810°K (2800°F). The principal limitation on temperature arises from the need to protect TZM from oxidation at temperatures above around 920°K (1200°F).

Data on the lifetime of TZM coated with molybdenum disilicide was obtained from reference 5. At the end-of-mission temperature of 1590°K (2400°F) which was selected as the basis for the design studies, a lifetime of 150-170 hr in still air is indicated. The actual coating lifetime will be determined by such additional factors as the influence of the pressure and velocity field over the nose cone, temperature gradients through the coating, and cyclic temperature operation.

COOLING SYSTEM DESIGN

A preliminary design of the heat pipe cooling system is shown in figure 3. The cooling system was designed for a peak cold wall heat flux of 3400 w/cm² (3000 Btu/ft²-sec), and a total heat load of 6640 kw-sec (6300 Btu). The system length is 61 cm (24 in.), and the half-angle of the lithium heat sink is 3.91 deg. The exposed surface of the TZM heat pipe is coated with molybdenum disilicide to prevent oxidation. The total cooling system weight is about 3.6 kg (8 lb).

The cooled surface extends beyond the nose tip to a small portion of the lateral nose cone surface, for a total axial cooled length of 3.28 cm (1.29 in.). This extension beyond the nose tip increases the heat load on the heat pipe cooling system, but is necessary to assure that the ablative layer will have a minimum thickness of 0.38 cm (0.15 in.) at its juncture with the forward end of the heat pipe.

The interior of the heat pipe is lined with a wire screen wick structure. The wick consists of two layers of different mesh TZM screen, of variable thickness. The wick is thinnest at the stagnation point, to minimize the temperature drop as heat flows through the wick thickness to vaporize the lithium in the wick pores at the inner wick surface. In the cooled region, the wick varies

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from a thickness of 0.046 cm (0.018 in.) at the stagnation point to 0.091 cm (0.036 in.) at the beginning of the heat sink section. The outer layer, which serves as the lithium flow channel, is fabricated from 100 mesh screen. The inner layer, which provides the necessary capillary pressure for circulation of the lithium heat pipe fluid, is constructed from 400 mesh screen.

The wick is considerably thicker in the heat sink section of the heat pipe, with a total thickness of 0.254 cm (0.100 in.). Here, the outer liquid flow channel is fabricated from 50 mesh screen, and is covered by a 400 mesh capillary pumping layer. The thicker wick also makes a significant contribution to cooling system thermal capacity.

Heat pipe heat transport limits were evaluated at the most severe heating condition, which occurs when the cold wall stagnation heat flux has peaked at 3400 w/cm² (3000 Btu/ft²-sec). At this time the hot heat pipe vapor has advanced about 36 cm (14 in.) into the heat sink section of the heat pipe. The calculations show that heat transport will not be constrained by limits imposed by: the attainment of sonic velocity in the heat pipe vapor, entrainment of the heat pipe liquid by its adjacent vapor, boiling of lithium in the heat pipe wick, or the maximum capillary pressure available in the wick pore structure.

During re-entry, the cooling system temperature reaches a peak of 1670°K (2550°F) at the stagnation point. The end-of-flight temperature is 2400°F. The internal cooling system pressure reaches a maximum value of 128,900 N/m² (18.7 psia), which is the vapor pressure of lithium at its maximum re-entry temperature of 1640°K (2500°F).

CONCLUSIONS

Heat pipe cooling, in conjunction with an appropriate sensible heat sink, constitutes a simple, effective technique for the thermal protection of stagnation regions without compromising the size and shape of such regions. The technique is applicable to missions of limited duration for which moderate total heat loads are experienced.

REFERENCES

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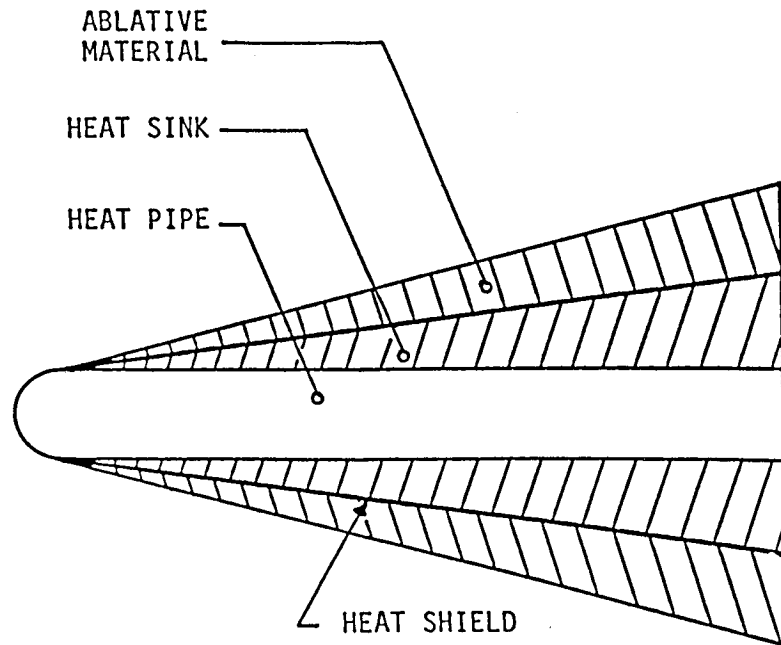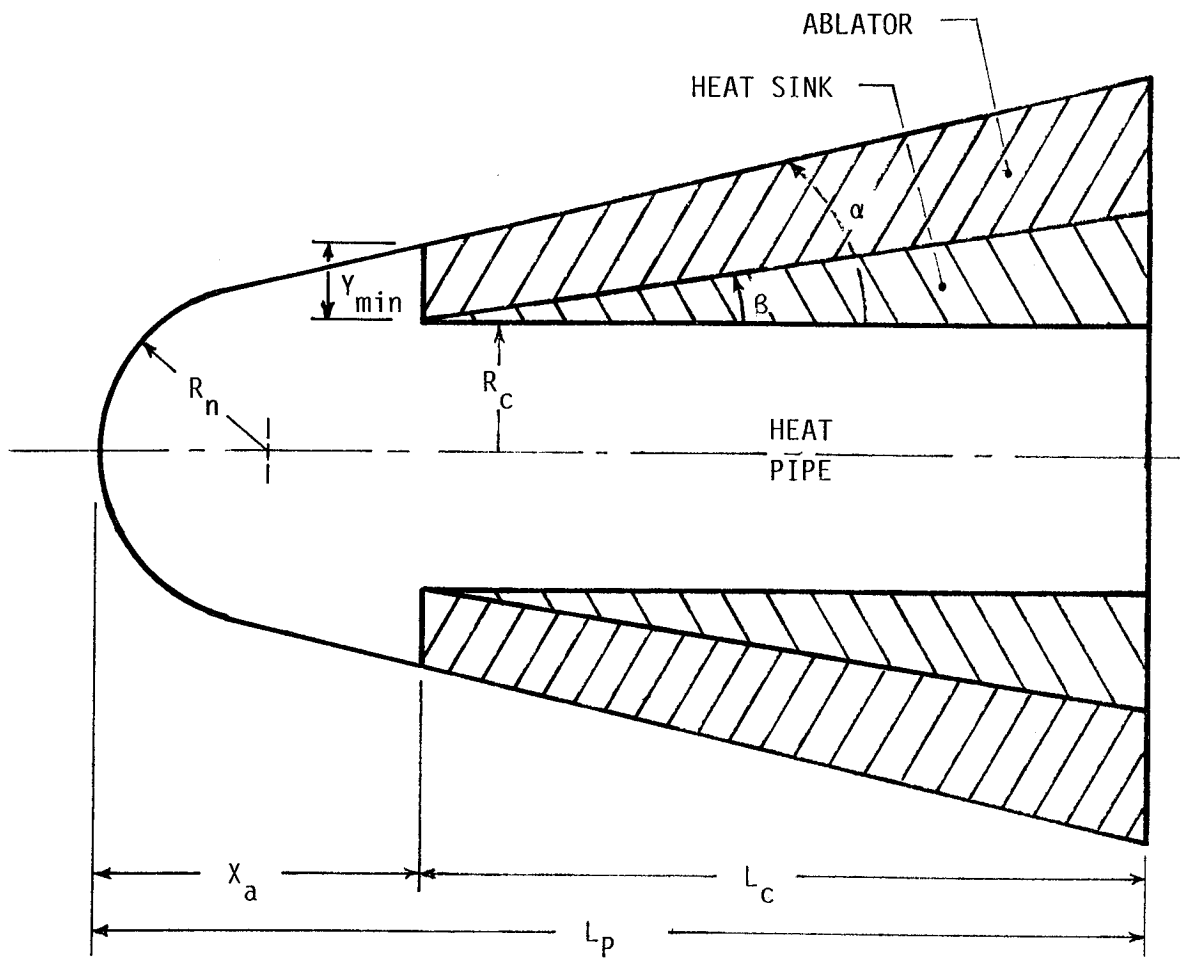
Figure 1. Basic Heat Pipe Cooling Concept for Nose Tip

R_n = nose radius

R_c = heat pipe radius in heat sink section

Y_{min} = minimum ablator thickness

α = nose cone half angle

β = heat sink half angle

X_a = axial cooled length

L_c = heat sink length

L_p = cooling system length
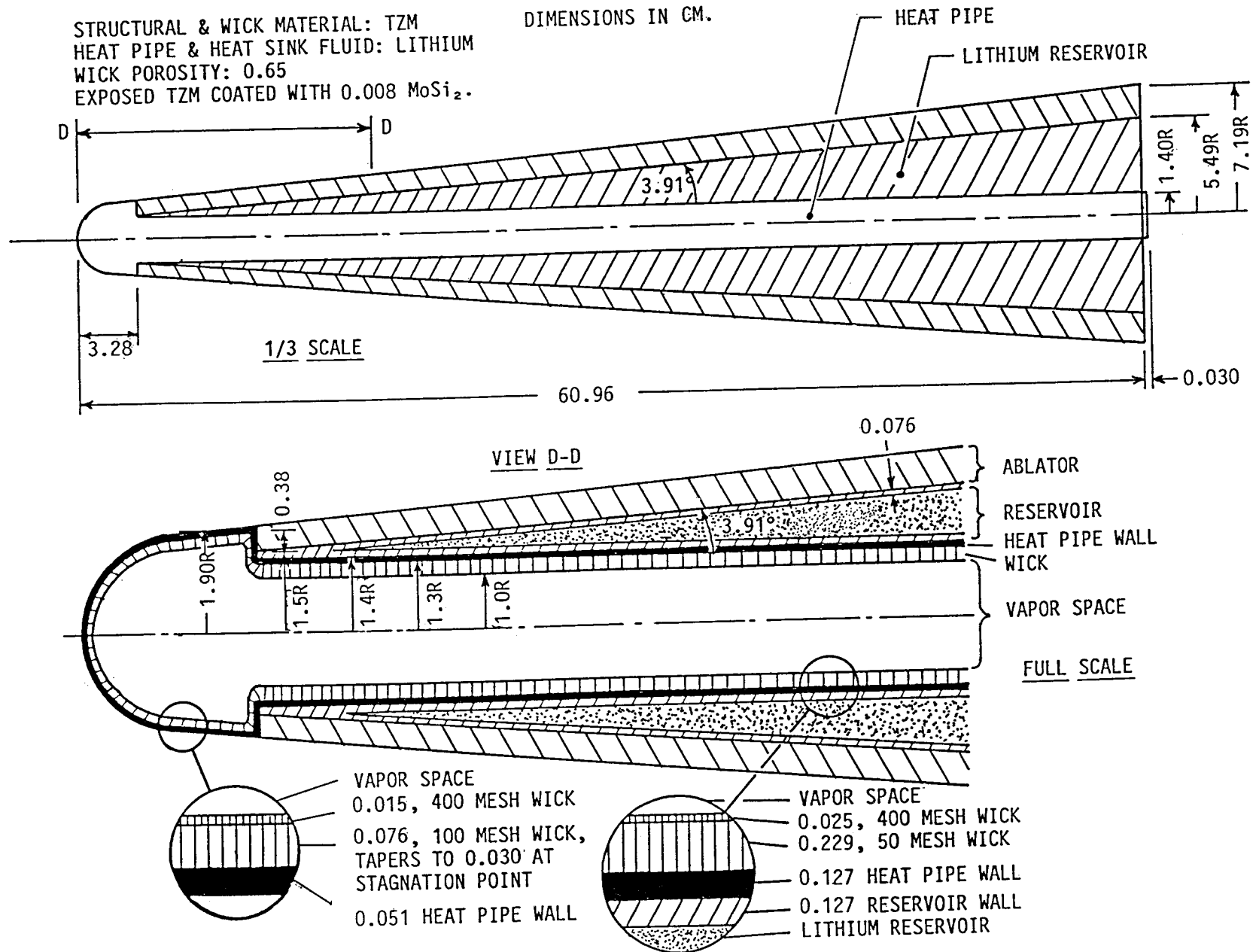
Figure 2. Geometry of Heat Pipe Cooling System

STRUCTURAL & WICK MATERIAL: TZM
HEAT PIPE & HEAT SINK FLUID: LITHIUM
WICK POROSITY: 0.65
EXPOSED TZM COATED WITH 0.008 MoSi$_2$.

DIMENSIONS IN CM.

HEAT PIPE
LITHIUM RESERVOIR

1.40R
5.49R
7.19R

3.91°

1/3 SCALE

3.28
60.96
0.030

VIEW D-D

0.076

0.38
1.90R
1.5R
1.4R
1.3R
1.0R
3.91°

ABLATOR
RESERVOIR
HEAT PIPE WALL
WICK
VAPOR SPACE

FULL SCALE

VAPOR SPACE
0.015, 400 MESH WICK
0.076, 100 MESH WICK, TAPERS TO 0.030 AT STAGNATION POINT
0.051 HEAT PIPE WALL

VAPOR SPACE
0.025, 400 MESH WICK
0.229, 50 MESH WICK
0.127 HEAT PIPE WALL
0.127 RESERVOIR WALL
LITHIUM RESERVOIR

Figure 3. Preliminary Design of Reference Sensible Heat Pipe Cooling System

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Session IX

THERMAL CONTROL
COATINGS AND MEASUREMENTS