Heat-Pipe-Cooled Leading Edges for Hypersonic Vehicles

Workshop on Materials and Structures for Hypersonic Flight
University of California Santa Barbara
July 12-13, 2006

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Agenda

♦ Introduction
♦ Modeling
♦ Fabrication and Testing
♦ Future Direction and Challenges
♦ Concluding Remarks
Heat pipes transfer heat isothermally by the evaporation and condensation of a working fluid.
Leading-Edge Heat-Pipe Operation

- Condenser: $T_s > T_{rad}$
- Evaporator: $T_s < T_{rad}$

Graph showing heat flux, Btu/ft²·sec vs position, in.

NASP ascent ($q_{max} = 495$ Btu/ft²·sec)

Shuttle Orbiter

Sharp LE, hypersonic vehicle

Upper surface

Lower surface

Position, in.
Heat Pipe Cooled Leading Edge History

- **Cal Silverstein** 1971
  - R=0.5"
  - Mach 8 Cruise Aircraft

- **C. Camarda** 1978
  - ½ scale Space Shuttle
  - Design, Fab/Test
  - Hastelloy x/Na

- **C. Wojcik** 1991
  - Nb-Zr/Li

- **Merrigan/Seng** 1989
  - Bench -scale Nose cap

- **NASP** 1990
  - Boman & Elias
    - 1990
    - Hastelloy-X/Na Heat pipe

- **C. Silverstein** 2001
  - Hypersonic
  - Engine Cowl
  - Mach 6 test

- **LMSSC_ AFRL/VA** 2005
  - Superalloy/Li;
  - Superalloy/Na; Mo-Re/Li

- **D. Glass et. al.** 1999
  - (Mo/Re)/Li Heat Pipe
  - Embedded in C-C
  - Fab & Test

- **2005/6**
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Heat-Pipe Modeling

♦ Conduction, convection, or radiation coupling to environment
♦ Container - conduction only
♦ Wick/working fluid - conduction and heat of fusion
♦ Vapor
  • Phase I - free molecular
  • Phase II - continuum front moves toward cooler end. Flow may be choked at end of evaporator
  • Phase III - continuum over entire length in vapor region Sonic limit not encountered
Heat-Pipe-Cooled Leading Edge Finite Element Analysis

$T_{\text{max}} = 2765^\circ\text{F}$

$T_{hp} = 2197^\circ\text{F}$

3-D finite element model (non-linear properties)
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♦ Introduction

♦ Modeling

♦ Fabrication and Testing
  • NASA
  • Air Force

♦ Future Direction and Challenges

♦ Concluding Remarks
NASA Langley Heat-Pipe Leading-Edge Experience

- Experience in design, analysis, integration, and testing

- Shuttle
  - Hastelloy-X
  - Na working fluid
  - Circular heat pipes

- NASP
  - Mo-Re embedded in C/C
  - Li working fluid
  - D-shaped heat pipes

- Advanced STS
  - Hastelloy-X
  - Na working fluid
  - Rectangular heat pipes
Heat pipes passively reduce leading-edge temperatures to reuse limits of composite refractory composite structure.

Mo-Re heat pipe lithium working fluid.
Description of Heat-Pipe-Cooled Wing Leading Edge

♦ Heat-pipe container
  • 0.010 in. arc cast Mo-41Re
    • High strength
    • High use temperature
    • Lighter than W-Re or pure Re
    • Ductile at room temperature
    • Weldable

♦ Heat-pipe working fluid
  • Lithium
    • 17 psia vapor pressure at 2500°F (1370°C)
    • Compatible with refractory metals

♦ Refractory composite structure
  • C/C or C/SiC (3-D woven fabric)
    • High use temperature
    • Lightweight
    • 0.010 in. SiC oxidation protection coating
    • CVD coating for minimization of coating temperature
Heat-Pipe-Cooled Leading Edge Development

- Numerous small specimens to study various issues

- Design validation heat pipe
  - 36-in-long straight heat pipe
  - Operated up to 2460°F (1350°C)
  - Throughput of 3.1 Btu/sec (3.3 kW)
  - Radial heat flux of 141 Btu/ft²·sec (160 W/cm²)
  - Developed leak due to difficulties with welded thermocouple

- Three straight heat pipes
  - 28-in-long
  - Operated up to 2300°F (1260°C) and 155 Btu/ft²·sec
  - Embedded in carbon/carbon
  - Testing to be performed at NASA LaRC

- J-tube heat pipe
  - 30-in-long
  - Nose and wick fabrication issues resolved
  - Transient performance tests at LANL
Heat-Pipe Fabrication and Testing
Design Validation Heat Pipe

- Container: 0.01-in. arc cast Mo-41Re, 0.3-in. radius
- Wick: 4 layers of 400 x 400 Mo-5Re screen
- Artery to reduce liquid pressure drop
  - 0.1-in. diameter, 400 x 400 mesh screen
  - Located on non-heated surface
  - Spring in artery for support
  - One end closed, pool at other end
- Heat pipe with thermocouples and induction heat coils
Steady State Heat-Pipe Operation

Design Validation Heat Pipe

Note: Thermocouples ~ 4 in. apart.
Heat-Pipe Start-Up From the Frozen State
Design Validation Heat Pipe

Induction heating

Heat pipe (~ 4-in. spacing)

TC #1 TC #2 TC #3 TC #5

Temp., °F

Time, sec.

TC 1 TC 2 TC 3 TC 5 TC 6 TC 7 TC 8 TC 9 TC 10

0 500 1000 1500 2000

0 500 1000 1500 2000

0 500 1000 1500 2000

0 500 1000 1500 2000

0 500 1000 1500 2000

0 500 1000 1500 2000

0 500 1000 1500 2000

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Comparison of the Three Heat Pipes
Three Straight Heat Pipes

Lithium, lb  Wet in

| Heat pipe #1  | 0.0099 | 42 hrs @ 1650-1740°F |
| Heat pipe #2  | 0.0088 | 70 hrs @ 1650°F     |
| Heat pipe #3  | 0.018  | 47 hrs @ 1650°F     |

- Heat pipe #1
  - 2300°F, 155 Btu/ft²-s over 1.5 in.
  - Nearly fully isothermal

- Heat pipe #2
  - 2420°F
  - @ 2075°F, non-condensible gas over last 6 in. of heat pipe

- Heat pipe #3
  - Never operated properly

28-in long
Heat Pipes Embedded In Carbon/Carbon
Three Heat Pipes in C/C

- Three Mo-Re heat pipes
- 3-D woven preform with T-300 fibers in a carbon matrix
  - increase through-the-thickness thermal conductivity
  - eliminate delaminations with 2-D C/C due to CTE mismatch
- No oxidation protection coating on C/C, therefore must test in an inert environment
C/C Heat Pipe Transient Testing

Three Heat Pipes in C/C

- Temp., °F
- Time, sec
- x = 30.0 in.
- x = 27.4 in.
- x = 2.9 in., under heaters
- Vertical, Horizontal
- 130 V
- 180 V
- x = 27.4 in.
- x = 30.0 in.
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Machine and Weld Nose Region
J-Tube Heat Pipe

Photograph of nose parts
Curved Wick Fabrication

J- Tube Heat Pipe

Wick formed on mandrel

Wick being formed around machined part

Nose portion of wick
RF-Induction Heating of J-Tube Heat Pipe

- RF-induction coil/concentrator heating of nose region on outer surface
- Test specific issue: Hot spot in nose region
  - Test
    - Curved surface not insulated, thus higher throughput required
  - Flight vehicle
    - Curved surface is “insulated”
J-Tube Heat-Pipe Checkout Tests

![Location of thermocouples](image)

**Start up of J-tube heat pipe**

**Maximum temperature distribution (not steady state)**

Test 1

Test 2

Test 3

Test 4
Test Induced Failure of Heat Pipe

- Nominal operation during 4 tests
- Test induced failure (concentrator arcing) during test 4
  - Insulation outgassed during test (~0.1 Torr)
  - Ionization between heating coil and heat pipe
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Overview: Heat Pipe Cooling for SOV Leading Edges AFRL/Lockheed Martin

♦ Identify Specific Operational Requirements, and SOV Configuration
  • Generated Performance Maps (Assuming Typical Requirements, and Configuration)

♦ Using LM-TSTO Orbiter Requirements, Developed Heat Pipe Cooled Leading Edge Designs for Moderate to High Heat Flux Cases
  • Heat Pipe Design Option
    – Modular Mo-Re Alloy Heat Pipe
    – Developed Processing approaches for Mo-Re/Li Heat Pipe Design
  • Heat Pipe Design Option
    – Modular Superalloy/ Li Heat Pipe
    – Successfully Designed, Fabricated, and Tested

♦ Developed Heat Pipe Design Solutions for Hypersonic Vehicles
  • Sharp Hybrid Leading Edge Designs
  • Cowl Inlet Cooling (Fabricate and Test Superalloy/Na Heat Pipe)

* First Superalloy/Li Heat Pipe
Performance Map for Heat Pipe Leading Edge Cooling

- Generated Relationship Between the **Cooling System Temperature** and Radiation Length and **Aerothermal Environment** for Different Leading Edge Radii
Technical Assessment of Key HPCLE Design Options

- **Key Design Options Very High Temp.**
  - Modular Mo Alloy/Li Heat Pipe
  - Modular (or D) Mo-Re/Li Heat Pipes Embedded in C-C or C/SiC
  - Modular (or D) Mo-Re/Li Heat Pipe Design

- **Key Design Options High Temp**
  - Superalloy/ Li Heat Pipe

- **Trade Study Criteria**
  - Materials Cost
  - Machining
  - Joining
  - Heat Pipe Durability
  - Thermal Performance
  - Structural Performance
  - System Weight
  - Life Cycle Cost
  - Manufacturing Yield
  - Start-up Risk
  - Atmospheric Protection Risk
  - Repair/Rework

- **Other System Level Concerns**
  - Impact From Atmospheric Debris
  - Oxidation Resistance
  - Thermal Contact Resistance
  - Robustness in Flight of Ground
  - Toxicity of Li, in Case of Leak
  - Manufacturing and Ease of Integration
  - Comparison with Passive and Actively Cooled Designs
Air Force Program Summary

♦ Developed Performance Maps Providing HPCLE Design Solutions

♦ Based on Analysis for TSTO-Based SOV Configuration
  • # 1 Modular Mo-47%/Li Heat Pipe
  • # 2 Modular Superalloy/Li Heat Pipe

♦ Performed Superalloy/Li Heat pipe Life Compatibility Tests
  • Successfully Demonstrated ~401 Hours Life

♦ Design, Fabrication and Testing of Prototype Articles
  • 4” x 36” Superalloy/Li Heat Pipes
  • Passed Functional Tests, Operational Performance Test (in Progress)

♦ HPCLE Design Development for Hypersonic Cruise Vehicles (Ongoing)
Additional Air Force-Funded Activities

♦ Refrac Systems - Norm Hubele (480) 940-0068
  • Wick/artery fabrication utilizing Mo-5Re alloy
  • Wick/artery insertion technique
  • Heat pipe container welding technique
  • Diffusion bonding methods
  • Modular heat pipe fabrication
  • Novel lithium fill method development
  • Alternate screen material evaluation

♦ MR&D – Brian Sullivan (610) 964-6131
  • Design and analysis of heat pipe cooled refractory composite leading edges

♦ Ultramet – Art Fortini (810) 899-0236 x118
  • Low cost CVD heat pipe fabrication

♦ Lockheed – Suraj Rawal (303) 971-9378
  • Small radius heat pipe cooled leading edge designs for hypersonic cruise vehicles
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Path Forward

♦ For heat pipes to be utilized on the leading edges of flight vehicles
  • Designers must be willing to insert the technology
  • The payoff must be significant and the technical evolution not

♦ High temperature heat pipe options
  • Superalloy or refractory metal
  • Embedded or not embedded

♦ Superalloy heat pipes offer increased heat flux capability to the designer using “conventional” materials

♦ Refractory metal heat pipes embedded in a refractory composite offer a significant increase in heat flux capability
Different Materials At Elevated Temperatures Are Problematic

- Material compatibility, f(t,T)
  - Problem: Brittle carbides, Carbon in heat pipe
  - Solution: Coating on Mo-Re

- Coefficient of thermal expansion mismatch (loose for stress, tight for thermal)
  - Problem: Buckling of flat surface, Increased contact resistance
  - Solution: Convex surface, Compliant or removable layer
Concluding Remarks

- Heat pipes can be used to effectively cool wing leading edges of hypersonic vehicles

- Heat-pipe leading edge development
  - Design validation heat pipe testing confirmed design
    - Three heat pipes embedded and tested in C/C
    - Single J-tube heat pipe fabricated and testing initiated

- HPCLE work is currently underway at several locations