Development of C-SiC ceramic compact plate heat exchangers for high temperature heat transfer applications

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AIChe Winter Meeting
San Francisco, CA
November 16, 2006
Review: Fabrication of plate type heat exchangers with chopped carbon fiber materials

- UCB proposed in 2004 that compact plate heat exchangers could be fabricated from inexpensive chopped-carbon-fiber based ceramic composites
  - Silicon-carbide fiber and woven carbon fiber too expensive

- Individual plates formed by die-embossing flow channels using a mold

- Assembly, pyrolysis, and infiltration can create complex, monolithic parts
  - Carbon fiber maintains dimensional stability during pyrolysis
  - Two possible infiltration processes: silicon melt infiltration (MI) and polymer infiltration and pyrolysis (PIP)

- Various coatings possible
  - CVD SiC and carbon
UCB is developing off-set fin plate heat exchangers: very large heat transfer area density and effective countercurrent flow

- Milled or die-embossed flow channel
- CVI/CVD carbon coated liquid salt surface
- CVI/CVD carbon coated helium surface
- Reaction-bonded joint

Liquid salt plate

Unit Cell

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LS and helium plates, and a complete HX module

liquid salt side plate

helium side plate
CVD coating of C/SiC coupons was demonstrated

- CVD coatings may be applied to interior HX surfaces after fabrication is complete (to be demonstrated in upcoming work)
Collaboration with ceramics specialists

• UCB collaboration with German Aerospace Center (DLR)
  – DLR MI C/SiC coupons have been tested for helium permeation and material mechanical properties by UCB and show very good results. Compact CVD SiC and Pyrolytic carbon coating to MI coupons has been successfully demonstrated. MI (Bioker) coupons have also been proven to resistant to HI corrosion by GA. Testing for phosphoric acid underway, testing for sulfuric acid planned.

• UCB collaboration with U.S. composite vendor COI
  – COI is providing composite material vendor support, mainly in fabricating test HX with PIP methods
    » successfully demonstrated the fabrication and pyrolysis of chopped carbon fiber reinforced, silicon-carbide polymer infiltrated and pyrolyzed (PIP) plates with high-quality millimeter-scale fins formed using teflon molds.
    » The teflon molds were proven to be reusable, so that the process clearly extrapolates to allow inexpensive mass fabrication of compact ceramic heat exchangers.
    » A stack of prototype test plates were successfully laminated and the processes are being refined.
Polymer Infiltration and Pyrolysis (UCB)
Tooling to produce molded plates from chopped fiber, SiC powder and polymer paste material

Teflon tools for forming plates and fins

Cured part prior to pyrolysis/lamination
Demonstrated fabrication of mm-scale fins with thru and blind (preferred) reusable teflon molds

1.5mm Thru

1.5mm Blind
Lamination and pyrolization of plates has been successfully demonstrated in a cross-flow HX geometry

- Success demonstrated viability of fabrication method
- Further process optimization is needed
  - Optimal lamination before or after initial pyrolization of plates?
  - Optimal surface preparation method for gluing plates together
  - Further reduce thickness of plate between finned regions

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Liquid Silicon Infiltration with Biomorphic SiC (DLR)
In-situ Joining during Silicon Infiltration (DLR)

- Creation of complex shapes
- Need for smooth surfaces prior joining
- Carbon based glue as precursor
- Complete carbon conversion required

Joining areas

Bad joining (fig. left)
Successful joining (fig. right)
High Temperature Plate Type Heat Exchanger in OSF Design

Prototype, machined from carbon plate prior to Si-infiltration

Prototype WBC plate with flow channels through molding
Fabrication Concept for gastight HX in OSF Design Using Wood Based Composites (WBCs)

1. Powder mixing and granulation
2. Near net shape pressing
3. Single plate joining
4. Pyrolysis
5. Si-infiltration
6. Surface coating
7. Quality assurance through NDE
Technology challenges for HX fabrication Using inexpensive WBCs as Semi-Finished Parts

- Improvement of powder mixing and granulation methods to enhance the materials homogeneity, especially in the green stage
- Near net shape manufacture by using improved pressing tools
- Development of reliable joining methods
- Improvement in accurate liquid silicon infiltration for compact HX
- Quality assurance of materials after each process step
Technology Readiness Level (TRL) for the Fabrication of Biomorphic SiC

- Fabrication of prototype components up to Ø 300 mm through plate machining and final pressureless silicon infiltration
- Near net shape pressing recommended with B1 material (low shrinkage)
- Parameters for pyrolysis and silicon infiltration carried out and fixed
- Work on reproducibility, process refinement and costs by using inexpensive wood composite technology more consequently
Developing Porous Media Models for Compact HXs
Thermal modeling of compact HXs

- **Object** - to develop comprehensive thermal/ mechanical models for compact HX at UC Berkeley by collaborating with UNLV - CFD & HT lab
- **Task** - to develop a global steady and transient state porous media model (PM) to predict the thermal & mechanical response of the IHX
  - Key focus: global thermal stress analysis for thermal transients
- **Four areas of study:**
  - **Local: UNLV - Fluent**
    » Convection coefficient varies on unit cell
    » Flow effects of rounded edge & gap between fins
  - **Global: UCB – porous media models**
    » 3-D steady state temperature, flow, mechanical and thermal stresses distribution at full HX scale based upon derived effective porous media properties
    » 3-D transient temperature, flow, mechanical and thermal stresses distribution
Modeling work finished so far

• **2-D transient heat transfer PM codes for IHX**
  – Concern only finned region of IHX
  – Hot and cold inlet conditions are given
  – Explicit & implicit algorithms were tried

• **Modes of heat transfer:**
  – Advection in hot fluid
  – Convection from hot fluid to fins
  – Conduction through solid
  – Convection from fin to cold Fluid
  – Advection in cold fluid
Computational region

- Begin with a simple model
  - Add complexity
- Fluent for global model
  - Transient capability
  - Variable properties
- PM model allows for smaller cells/calculation time/other parameters
- PM model restricted to global analysis, neglecting local phenomenon
Longitudinal (flow direction) transient temperature profile for the ceramic solid (conduction layer) in the IHX
Summary

• **Polymer Infiltration and Pyrolysis (PIP) fabrication of compact heat exchanger demonstrated, remaining issues include**
  – Process control improvements to reduce residual porosity
  – Improved lamination method
• **Liquid Silicon Infiltration (LSI) with Biomorphic SiC**
  – Refine methods for fabrication using molds
  – Demonstrate lamination and infiltration
• **CVD coating of internal heat transfer passages**
  – Work to demonstrate SiC and pyrolytic carbon coating to be performed
• **Transient thermal/mechanical response of compact heat exchangers using porous media approximation**
  – Successfully applied to estimate mechanical stresses
  – Development of transient thermal response model underway