Fabrication of Microchannel Chemical Reactors using a Metal Lamination Process

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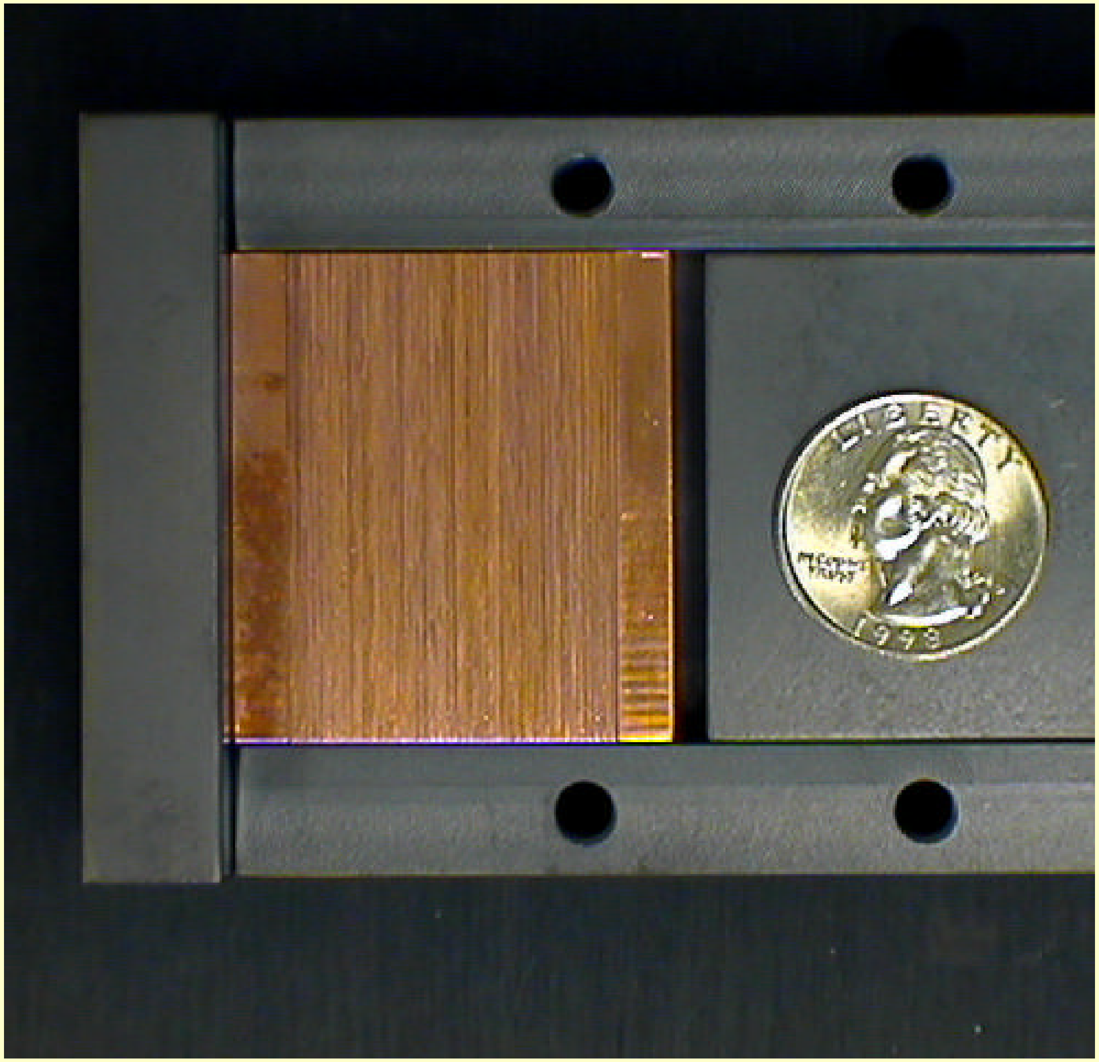
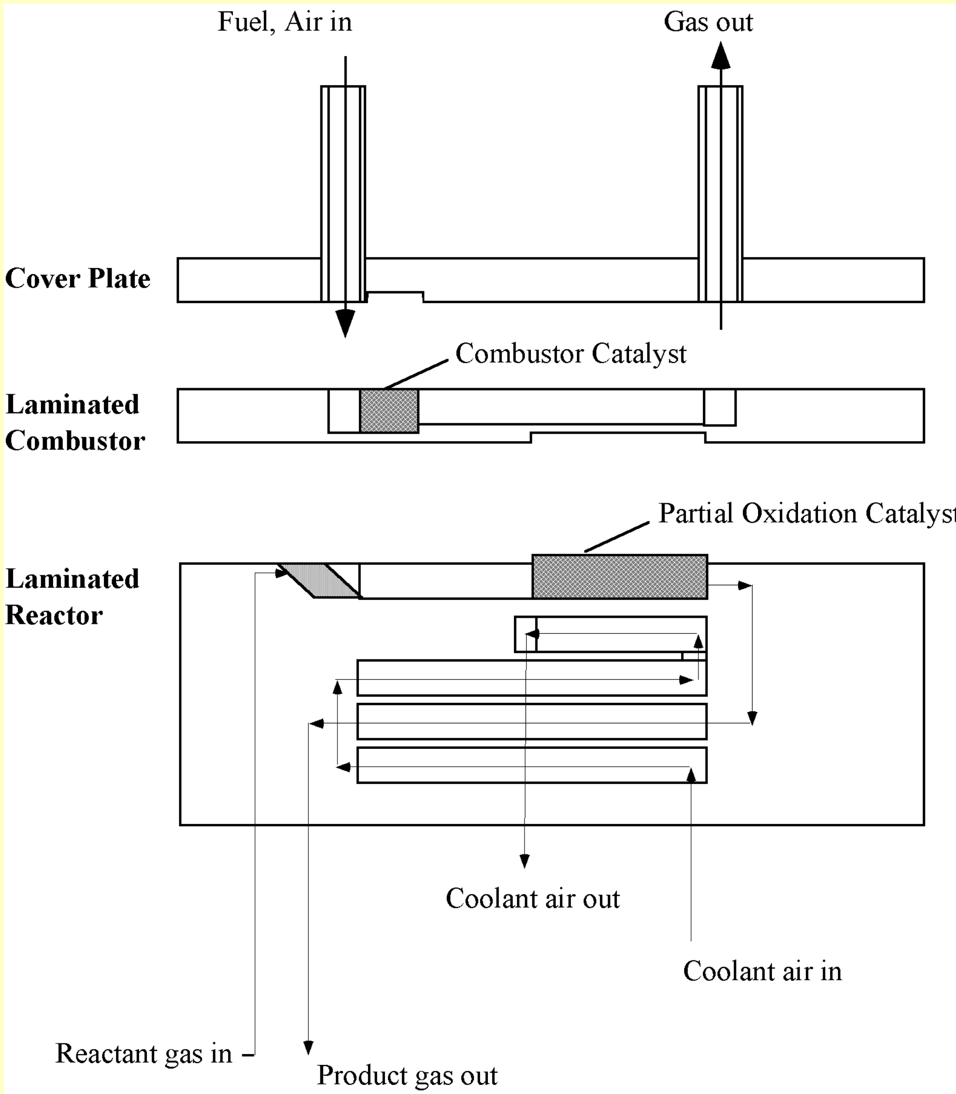
Stack of Shims in Clamping Device Prior to Bonding



Gas Flowpath Diagram for the Laminated Microchannel Combustor/Reactor



Application of Microchannels in Small-Scale Chemical Processing Devices

- High temperature small-scale chemical processing devices have unique thermal management challenges
- Microchannel designs can promote heat transfer in microscale devices
  - » expanded thermal contact area
  - » internal (fluid/fluid heat transfer)
  - » external (heat transfer to air through microchannel fins)

Desirable Properties for Small-Scale Chemical Processing Devices

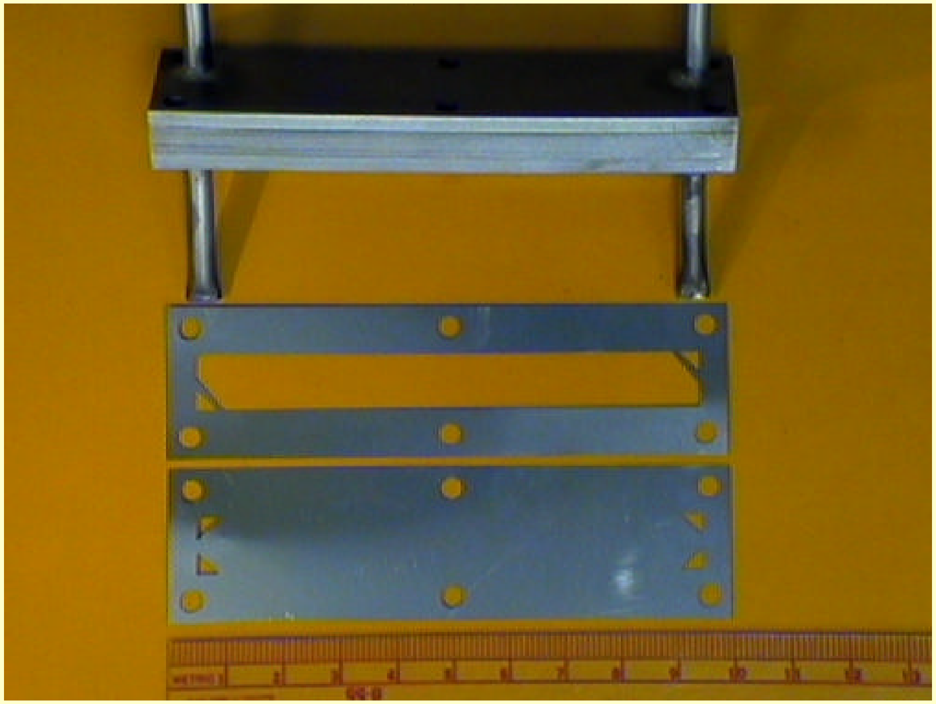
- **Metal body**
  - » high temperature and/or high pressure applications
  - » thermally conductive
  - » robust
  - » corrosive fluids
- **Leaktight**
  - » gaseous reactants/products
  - » liquid coolants
- **Efficient thermal management**
  - » microchannel arrays
- **Low cost**

Summary

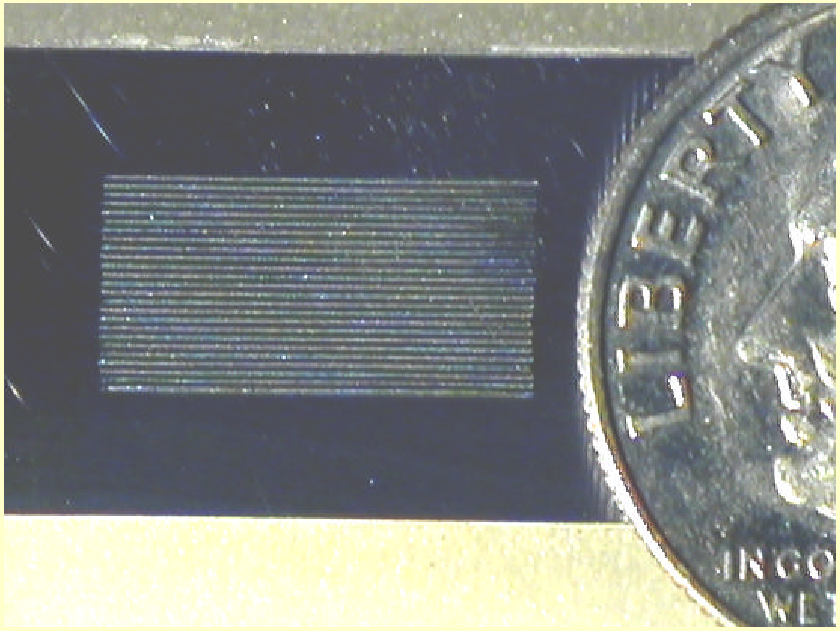
- Applications exist for small-scale high-temperature chemical processing devices
- Internal microchannels can be used for thermal management in metal devices
- Unique microchannel reactor designs are possible using lamination/bonding processes

Laminated Stainless Steel Microchannel Devices

Laminated stainless steel test device and shims used to fabricate it



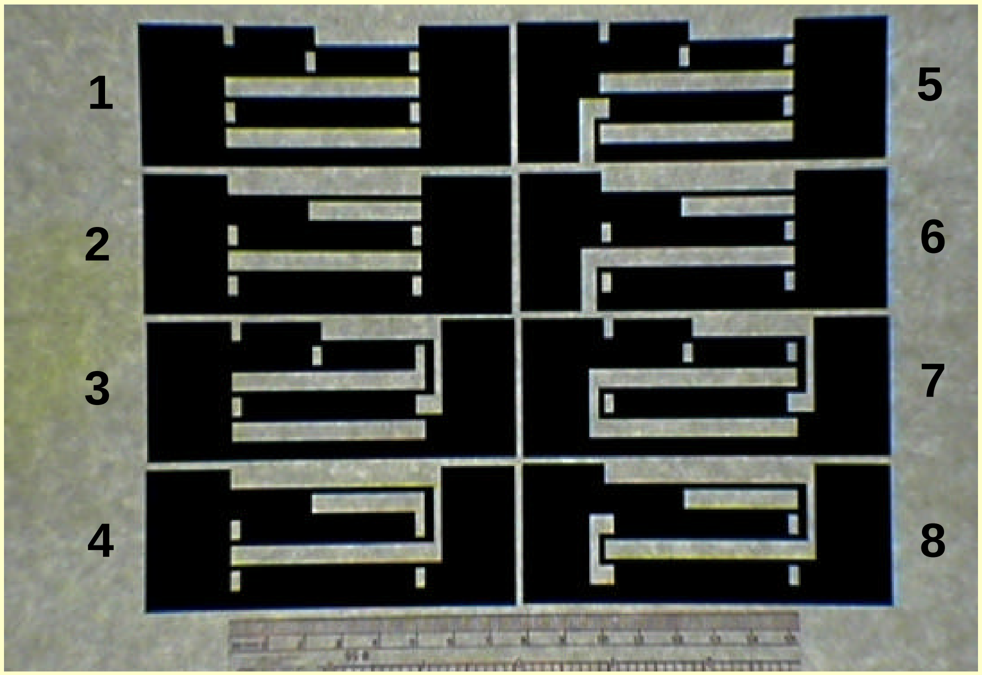
Cross section of microchannels within laminated test device



Potential Applications for Microscale Chemical Reactors

- Man-portable heating/cooling units
- Fuel processing devices
- Remote chemical processing units
- Space missions
- Point-of-use production of hazardous chemicals

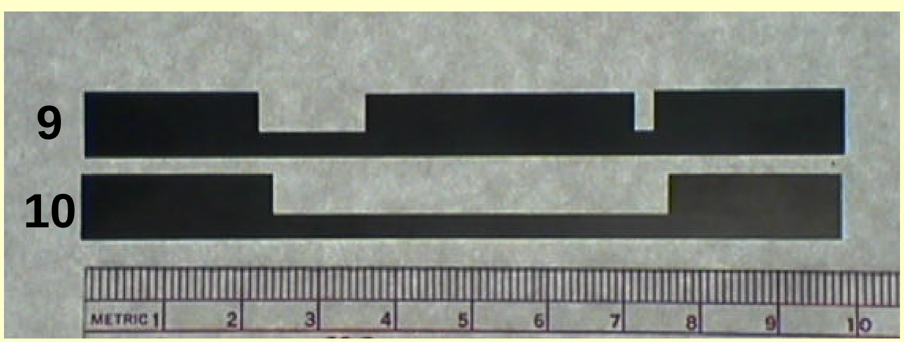
Shim Designs and Stacking Order for Laminated Combustor/Reactor



All shim material: 0.010” (250 μm) type 316 stainless steel

Shim assembly order for laminated reactor:

1) solid endblock
2) 12 ea #3, 13 ea #4 alternating
3) 26 ea #1, #2 alternating
4) 8 ea #5, #6 alternating
5) 26 ea #1, #2 alternating
6) 12 ea #7, 13 ea #8 alternating
7) endblock with coolant outlet



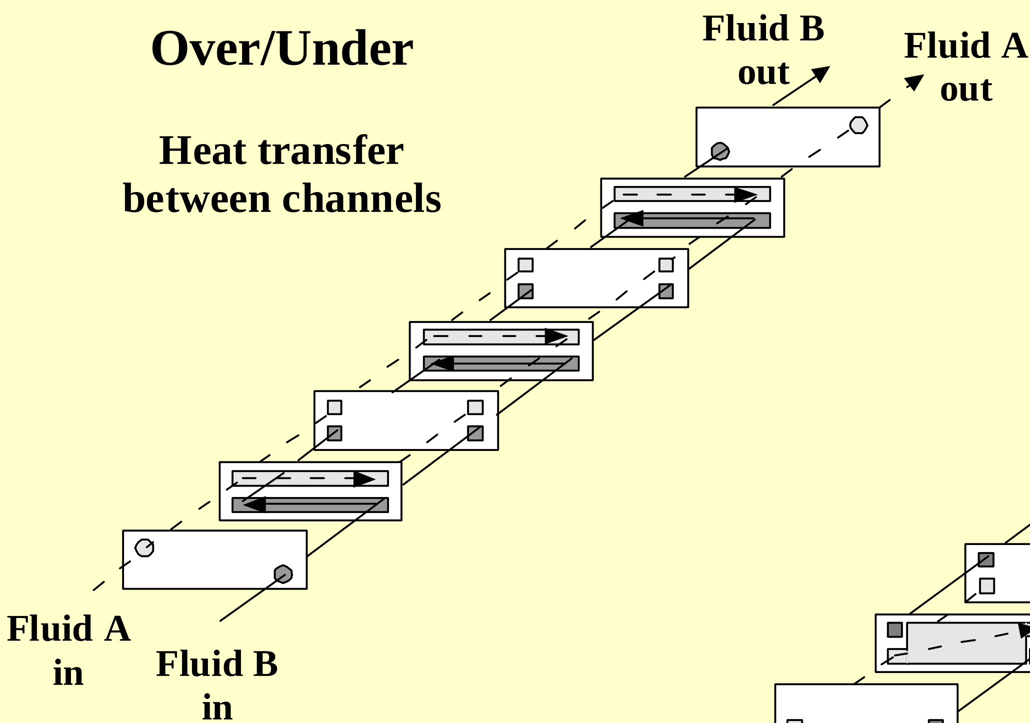
Shim assembly order for laminated combustor:

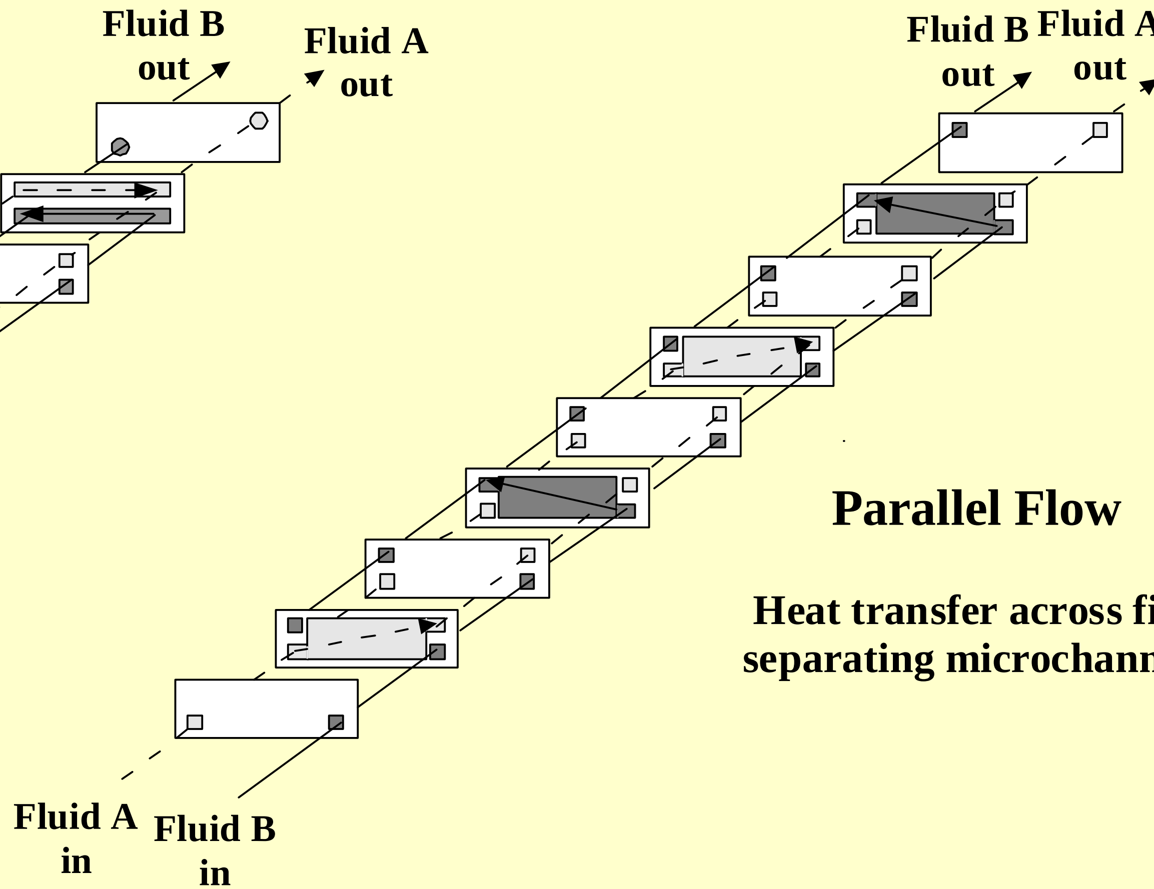
1) solid endblock
2) 85 ea #9, #10 alternating
3) solid endblock

Generic Microchannel Heat Exchanger Designs

Over/Under

Heat transfer between channels

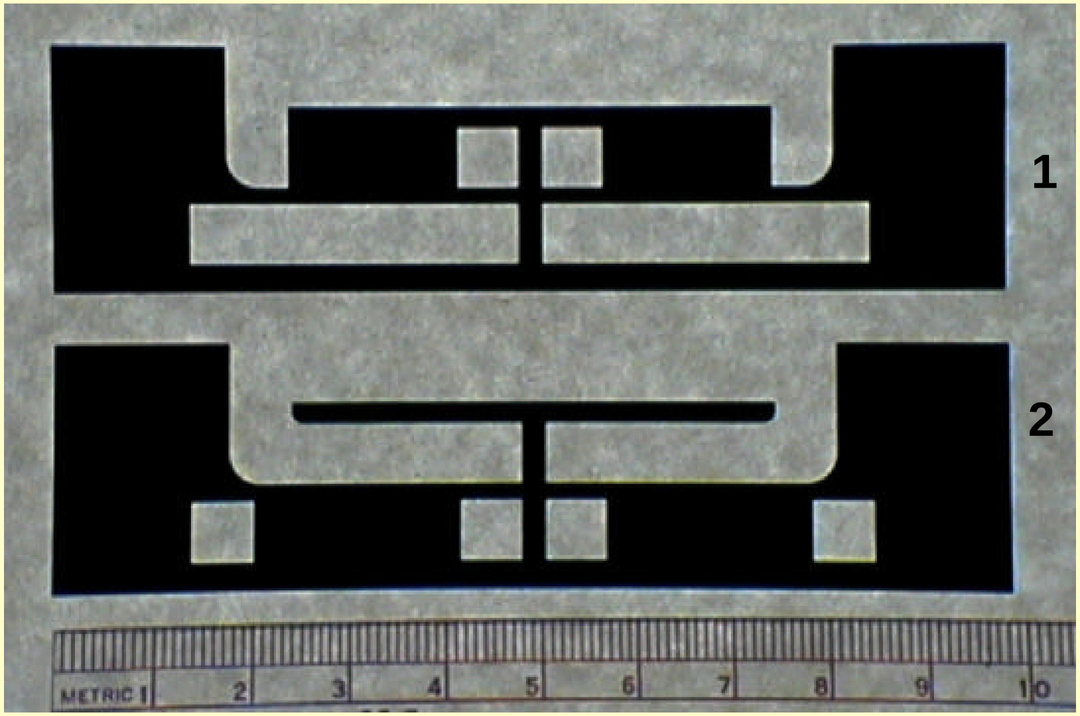




Parallel Flow

Heat transfer across fins separating microchannels

Shim Design and Assembly Order for Laminated Microchannel Fuel Vaporizer



1

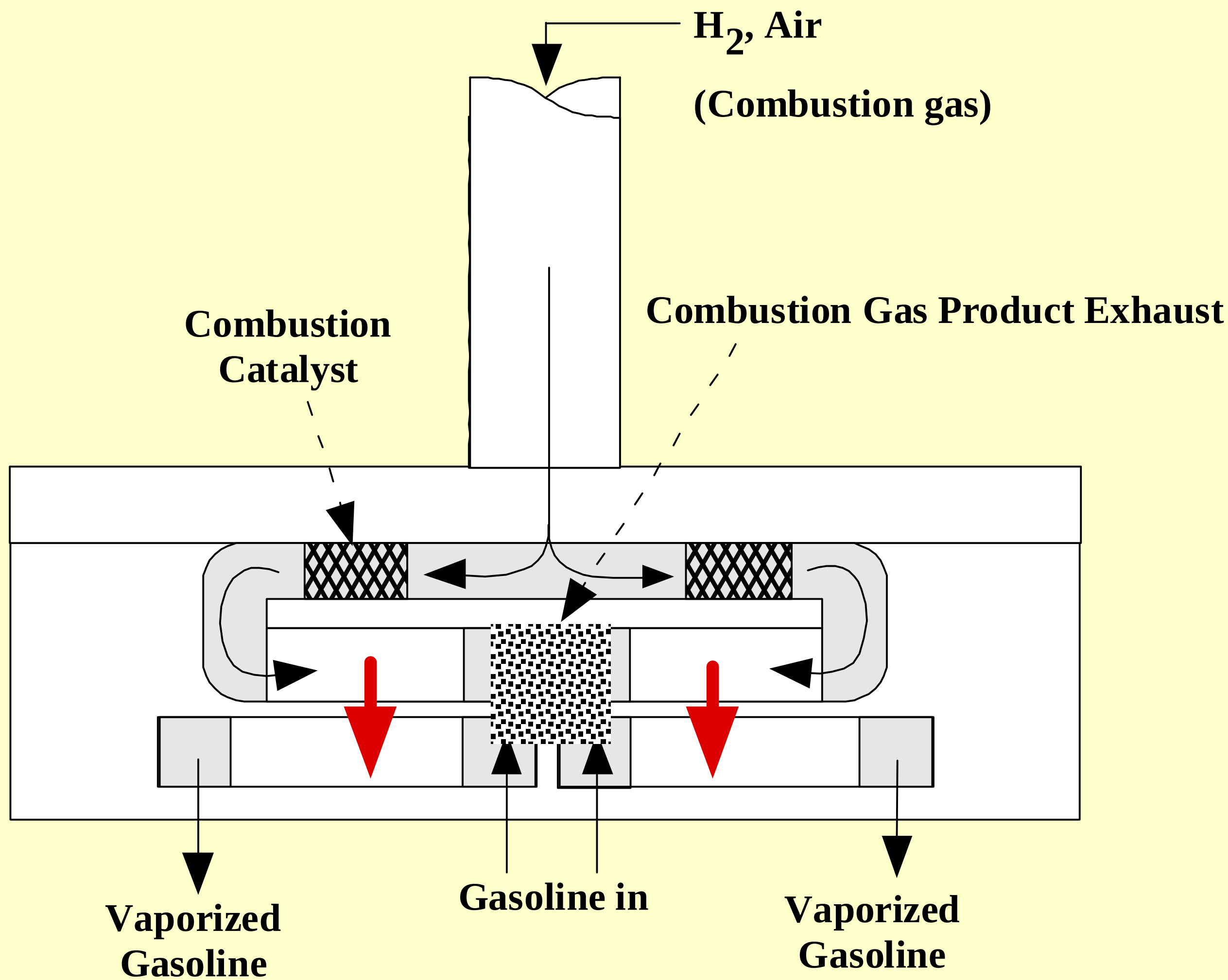
2

Assembly order for stainless steel microchannel fuel vaporizer:

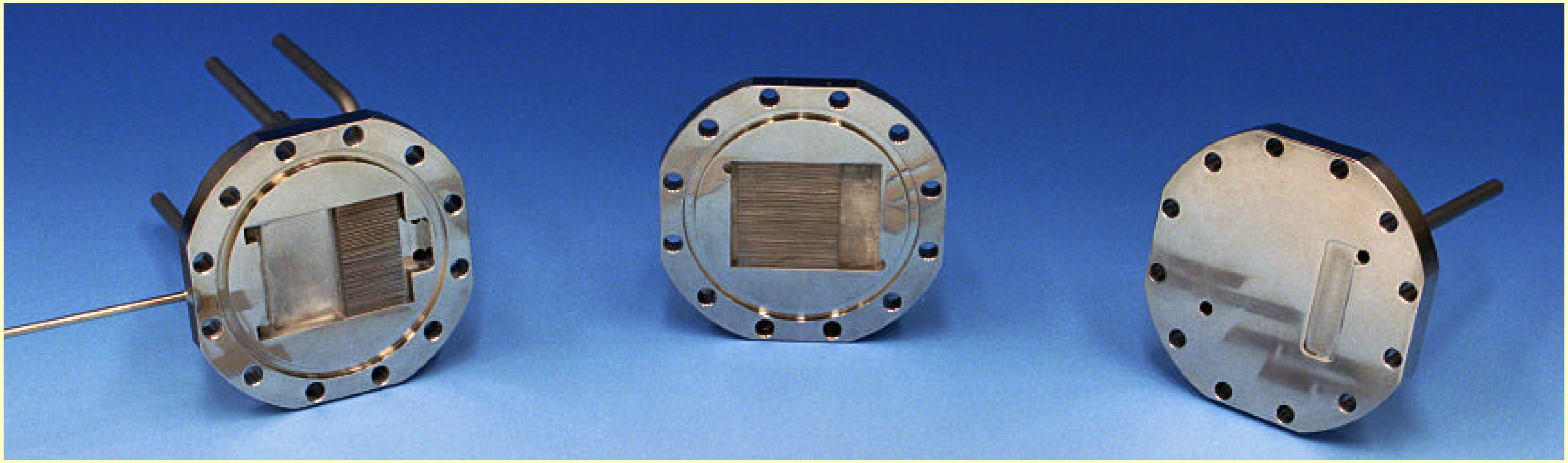
1) **solid endblock**
2) **134 ea shim #1, shim #2 alternating**
3) **solid endblock with combustion gas exhaust port, gasoline inlets and outlets**

Material: 0.010" (250 µm) 316 stainless steel

Flow Pattern in Laminated Microchannel Gasoline Vaporizer



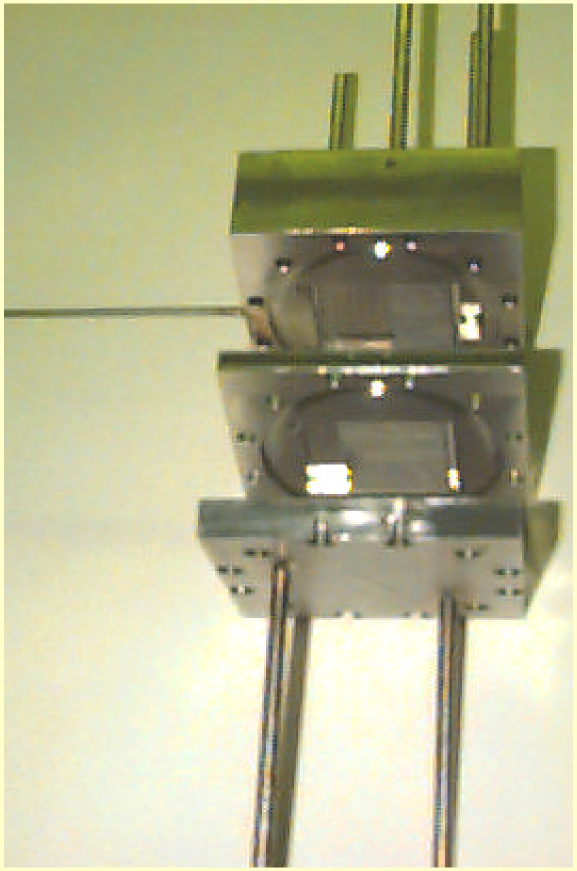
Laminated Microchannel Combustor/Reactor Components After Final Machining



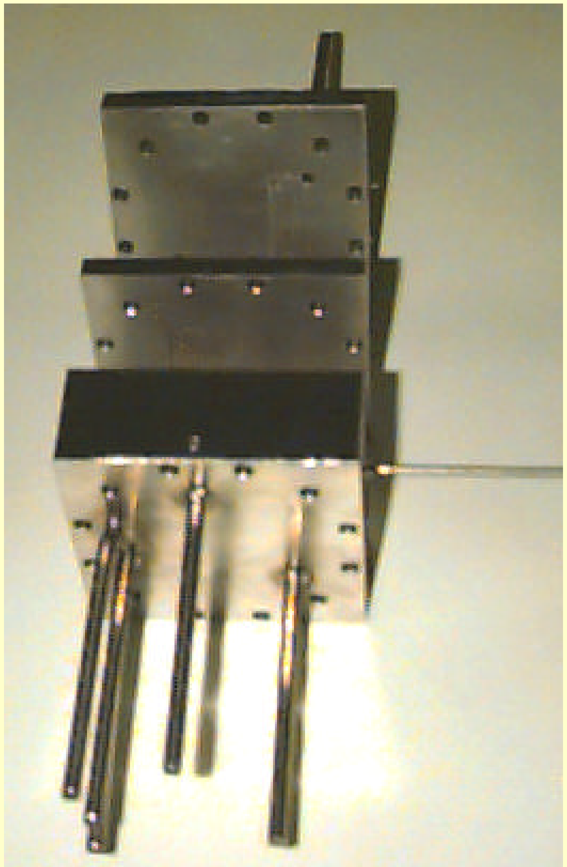
Reactor Combustor Top Plate

Laminated Microchannel Reactor/Combustor Before Final Machining

Top View



Bottom View



Dimensions (minus tubes): 10 cm x 10 cm x 5.6 cm

Post-Bonding Processes

- **Machining**
  - » mass/volume reduction
  - » incorporate fluid connections (fittings)
  - » add sealing ring grooves or other sealing surfaces
  - » drill bolt holes for clamping
  - » aesthetics
- **Welding/brazing**
  - » tube connections

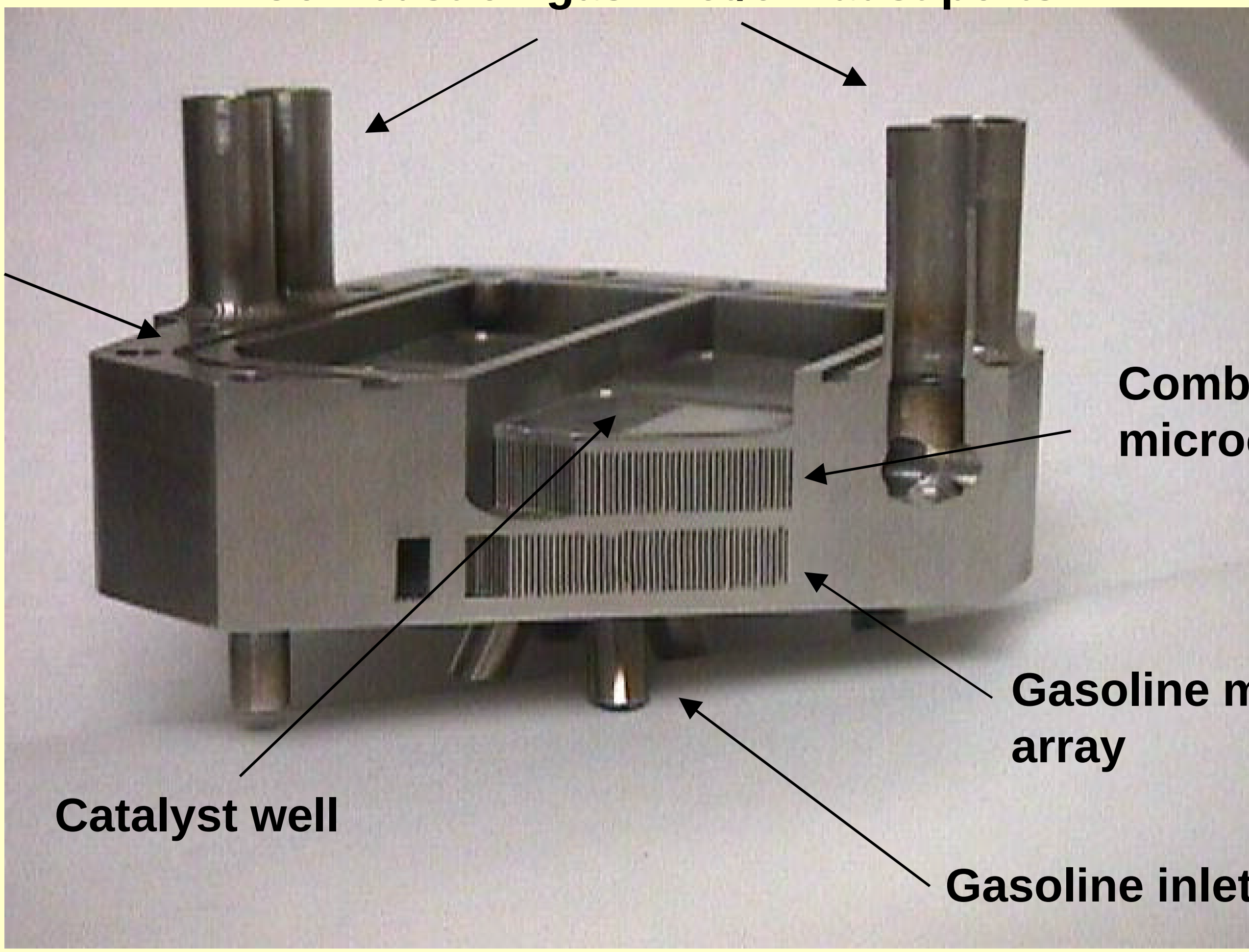
Microchannel Array Device Fabrication Steps

- Design device
- Pattern metal shims
- Clean and assemble shims
- Bond shims into solid device
- Post-bonding processes

Shim Patterning for Laminated Devices

- **Requires low cost, clean, burr-free patterned shims**
  - » photochemical etch process
  - » stamping
  - » laser machining (?)
- **Endblocks are typically mechanically machined from heavier stock**
  - » may incorporate vertical flow channels between levels
  - » may contain fluid interconnects

Cutaway View of Laminated Stainless Steel Gasoline Vaporizer



Cleaning/Assembly and Diffusion Bonding Conditions for Laminated 316 SS Reactors

- Degrease shims and endblocks
- Stack in Inconel clamp
- Bonding conditions:
  - » vacuum
  - » 4000 psi (27.6 MPa)
  - » 920-950°C
  - » 4 hr
- Alternative bonding methods
  - » diffusion brazing
  - » ultrasonic bonding

Design of Laminated Microchannel Devices

- Utilize laminate fabrication method to incorporate microchannel arrays, multilevel architecture, vertical flowpaths
- Avoid open internal areas behind critical seal surfaces
- Design devices as multiple components if internal areas need to be accessed
- Use pre- or post-lamination processes for external features
  - » sealing ring grooves
  - » bolt holes
  - » fluid inlet/outlet ports

Microchannel Arrays in Metal Devices

Microchannels: flow channels having at least one dimension $\leq$ 250 microns

- **Promote directional heat transfer in small areas**
- **Difficult to produce in metals using conventional machining processes**
- **Impossible to machine internally in metal devices**

Advantages of Lamination Process for Microchannel Device Fabrication

- **Solid, leaktight, all-metal product suitable for post-bonding processes**
  - » machining
  - » welding
  - » brazing
- **Production of internal microchannel arrays not possible using other fabrication methods**
- **Low cost compared with other microchannel fabrication methods**