Review of Fractal Heat Exchangers
Paper 2384

Zhiwei Huang, Yunho Hwang,
Vikrant Aute, Reinhard Radermacher

Center for Environmental Energy Engineering,
Department of Mechanical Engineering,
University of Maryland,
College Park, MD, 20742-3035, USA
Contents

- Introduction
- Fractal theory
- Major findings
- Research trends and gaps
- Conclusions
- Future work
Introduction

From nature to engineering:

- Fractal geometry:
  - Respiratory systems and vascular systems of plants and animals
  - Intrinsic advantage of minimized flow resistance and strong heat transfer capability
Fractal Theory

- Murray’s law (Murray, 1926):
  - Total work = pumping power + energy to maintain blood volume
  - \[ r_p^3 = r_1^3 + r_2^3 + r_3^3 + \cdots + r_n^3 \]

- Scaling law (West, 1997):
  - \[ Q \sim M^{3/4} \]
  - \[ r_p^2 = r_1^2 + r_2^2 + r_3^2 + \cdots + r_n^2 \]

- Constructal theory (Bejan et al., 1996, 2008):
  - Heat transfer
  - Direction

Bejan and Lorente (2006)
Geometries

(Pence, 2002) (Chen and Cheng, 2002)

(a) (b) (c)

Fig. 5. Sketch of a micro heat exchanger.
(Chen and Cheng, 2002)

(Wang et al., 2007)

(a) $\theta = 30^\circ$
(b) $\theta = 60^\circ$
(c) $\theta = 100^\circ$
(d) $\theta = 140^\circ$
(e) $\theta = 180^\circ$
(f) $\theta = 180^\circ \pm 180^\circ$

FIG. 4. (Color online) Velocity contours for various angles $\theta$. 
Model Assumptions

Common assumptions:
- Laminar flow and negligible heat loss to environment (1);
- Negligible gravity (2);

Specific assumptions:
- Fully developed/developing flow in channel (3a/3b);
- Negligible/non-negligible loss at bifurcation (4a/4b);
- Constant/temperature dependent properties (5a/5b);
- Constant heat flux at channel wall/constant temperature with adiabatic top/constant heat flux at bottom plate and conjugated heat transfer of wall. (6a/6b/6c)
Performance

Compared with serpentine channels, fractal channels have:

- Larger heat transfer capability
- Lower pressure drop (50%, Senn and Poulakakos, 2004)
- More uniform temperature on the heating surface

(Chen et al., 2010)
Performance

Compared with parallel channels, fractal channels have:

- Larger heat transfer capability (30°C lower wall temperature, Pence, 2002)
- More uniform temperature on the heating surface (75% lower temperature variation, Alharbi et al., 2004)
- Lower pressure drop (60%, Pence, 2002) / pressure drop penalty (10%, Alharbi et al., 2004)

(Wang et al., 2006)

Pressure drop penalty

(Wang et al., 2007)

8.8 kPa for parallel channels
Mechanism

- Boundary layer reinitiate at bifurcations results in recovery in pressure and Nu.
- Secondary flow motions initiated at bifurcations (longitudinal vortices, transverse vortices), causing laminar mixing which improves local Nu;
- Not fully developed flow in higher branching level also results in lower pressure drop.

(Wang et al., 2006)  
Senn and Poulikakos (2004)
## Design Parameters

<table>
<thead>
<tr>
<th>Design factors</th>
<th>Change</th>
<th>Values</th>
<th>Publication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>Increase</td>
<td>• Heat transfer capability increases • Pumping power decreases • Temperature uniformity increases</td>
<td>Chen and Cheng, 2002</td>
</tr>
<tr>
<td>Total number of branching levels</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bifurcation angle</td>
<td>Increase</td>
<td>• Pressure drop increases • Distribution uniformity of outlet mass flow rate increases • 30° is optimal angle</td>
<td>Want et al., 2007</td>
</tr>
<tr>
<td>Aspect ratio (AR)</td>
<td>Increase</td>
<td>• COP decreases • Ratio of COP over COP of straight channels increases</td>
<td>Yu et al., 2012</td>
</tr>
<tr>
<td>Confluence /diffluence flow</td>
<td>Confluence flow</td>
<td>• Pressure drop is larger • Difference is insignificant</td>
<td>Chen et al., 2012, 2015</td>
</tr>
</tbody>
</table>
Research Trends and Gaps

Modeling:
- 1-D, 2-D, 3-D
- Assumptions tend to be more complicated and closer to reality
- Mostly are steady state simulation, few investigated transient heat conduction (Chen et al., 2015).

Experiment:
- Most focus on thermal and hydraulic performance of channels, few investigated adiabatic flow boiling (Daniels et al., 2011) and utilized flow visualization (Guo et al., 2014).
- Conflict results, design factors like branch angle and AR should be comprehensively studied.
Application:

- Heat sink
- Flow distributor/collector
- Tube & shell HX
- Fin
- Fuel cell, reformer
- Spindle cooling
- Thermoelectric material

Types of Heat Transfer:
- Gas to gas
- Liquid to liquid
- Liquid to gas
- Solid-to-liquid/two phase
- Solid to gas
- Solid to solid
Research Trends and Gaps

Traditional shape optimization method:
- Low design freedom
- Strongly depends on initial setting
- Do not change topological structure

Topology optimization:
- Material distribution problem
- Boundary appear and vanish during optimization

Example:
- Objective: maximum heat transfer rate
- Initial conditions:
  - $\Delta T = 40$ K
  - $\Delta p = 10$ kPa

<table>
<thead>
<tr>
<th>D: fixed design domain</th>
<th>$\Omega$: fluid domain</th>
<th>$\Gamma$: boundaries</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T = 40$ K</td>
<td>$\Delta p = 10$ kPa</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Height (mm)</th>
<th>$\dot{Q}$ (W)</th>
<th>$R_{hs}$ (K/W)</th>
<th>$\dot{m}$ (g/s)</th>
<th>$\dot{m}c_p$ (W/K)</th>
<th>$hA$ (W/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully open channels</td>
<td>0.5</td>
<td>12.3</td>
<td>3.25</td>
<td>101</td>
<td>421</td>
</tr>
<tr>
<td>Optimal design</td>
<td>0.5</td>
<td>794</td>
<td>0.0504</td>
<td>8.88</td>
<td>37.1</td>
</tr>
</tbody>
</table>

(Yaji, 2015)
(Oevelen and Baelmans, 2014)
Conclusions

- Reviewed fractal heat exchangers

**Advantages of fractal channels:**
  - Higher heat transfer performance
  - Lower pressure drop
  - More uniform temperature

**Mechanism is the reinitiate of boundary layer at bifurcation.**
Future Work

- Transient simulation.
- Most research are analytical or numerical. More experiments should be done.
- Most designs are not optimal, leading to unfairness of comparison and conflictive results. Factors like branch angle and AR should be further studied to optimize designs.
- No research has been conducted to liquid-to-gas, gas-to-gas heat exchangers.
- Gradually developing topology optimization method should be investigated more.
ACKNOWLEDGEMENT

This work was supported by the United States Department of Energy Grant Number DE-EE0006114, and the Center for Environmental Energy Engineering (CEEE) at University of Maryland.

Thank you