UNCONVENTIONAL PERMEABLE MICROSTRUCTURES
AN ENGINEERED POROUS MATERIAL

Designing the microstructure of a dynamic insulation component using additive manufacturing and evaluating its effect on air flow rate and pattern

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P5 Presentation
OVERVIEW
40% Total primary energy consumption

30% CO₂ emissions

Costa, Keane, Torrens & Corry (2013)
www.thenounproject.com
Increased buildings’ energy use

- Climate change
- Population growth
- Increased demand for building functions

Cao, Dai & Liu (2016)
www.thenounproject.com
HVAC systems, Europe

- Building energy consumption: 50%
- Global energy consumption: 10-20%

de Gracia (2019)
www.thenounproject.com
The major potential of the building sector in saving energy cannot be ignored.
Efficient design of the building envelope
Responsive building elements (RBE)

Optimum interior conditions

Environmental performance

Design solutions

www.thenounproject.com
Van der Aa, Heiselberg & Perino (2011)
Features of responsive building elements

1. Dynamic behavior
2. Adaptability
3. Ability to perform various functions
4. Intelligent control

www.thenounproject.com
Van der Aa, Heiselberg & Perino (2011)
Dynamic insulation

Winter

Outside

Inside

Contra-flux mode

Summer

Outside

Inside

Pro-flux mode
Performance of dynamic insulation
PROBLEM STATEMENT
Air velocity highly affects the performance of the system

In the current literature, specific requirements are not mentioned for the air velocity to reach optimum performance of dynamic insulation.
“An increasing air velocity from outside through the wall, reduces the capability of the component to dampen and shift the external temperature wave”

Alongi, Angelotti & Mazzarella (2019)
Geometry can have a significant impact on air flow and heat transfer.

It is possible to expect that the geometry of the insulation’s pores affects the velocity of the incoming air.
Yet, this influence is not investigated in the current design.
Studies on complex geometric configurations are needed.
Production of **complex geometries**

Potentials of additive manufacturing are not explored in the design of dynamic insulation at micro-scale.
Discovering whether and how a designed microstructure can offer a solution for controlling the air passing through dynamic insulation and therefore, improving the performance of the dynamic insulation
RESEARCH QUESTION
How can complex microscale geometries contribute to regulating the air flow rate and pattern inside dynamic insulation, using the potentials of additive manufacturing?
What are the complex geometries? How can they be generated and how can their properties be evaluated?

Why implementing complex geometries in the design of a dynamic insulation could offer a potential contribution to the performance of the system?
What is the effect of texture on the air flow rate and pattern?

What is the effect of surface roughness on the air flow rate and pattern?

What is the effect of the geometry's changing cavity volume and morphology of the air channels on the air flow rate and pattern?
What is the potential contribution of additive manufacturing to this process and research?
DESIGN THROUGH RESEARCH
Static pores might not be an efficient design
For the dynamic insulation to be able to respond to the changes of the outside velocity, it has to have a variable ventilation performance.
How?
By having an adaptive cavity volume

Cavity
Representing the pores in a conventional porous material
Transportation of fluids is done through the cavities.

Porosity
“Ratio of the cavity volume to the total volume”

\[
\phi = \frac{\text{Cavity volume}}{\text{Total volume}}
\]

Permeability \((K_a)\)
A measure of the ability of a material to transmit fluids.
Due to the dynamic characteristics of air flow, permeability should not be constant in the design of dynamic insulation.
If $K_a$ constant
If $K_a$ constant

Permeability is not dependent on position

Wit, 2009
If $K_a$ constant

Permeability is not dependent on position

Higher pressure drops $\rightarrow$ Higher airflow rates.

Wit, 2009
Flow of air in any environmental condition

Permeability should not only depend on position, but also on another parameter that can be controlled, air flow rate.

Air flow rate should become independent of the pressure difference over the facade

Target phenomena
A self-regulating system

The geometry **adapts** itself to the incoming air velocity

Providing an **almost constant flow rate**
A fluid-microstructure

Interactions occur between a **moving/deformable structure** and a **fluid flow**

These interactions can be **stable** or **oscillatory**
Target microstructure

Adapting to the incoming air

Having varying cavity volume over time
Basis of geometry generation

Functionally Graded Materials  Metamaterials
Basis of geometry generation

**Functionally Graded Materials**

Exist in nature

Have **gradually-changing porosity, microstructure or chemical composition** over the entire volume of the material

The varying properties of the material **depend on the spatial position in the geometry**

Resulting in **having particular functions** and performance

**Metamaterials**

Miyamoto, Niino & Koizumi, 1997, as cited in Mahamood & Akinlabi, 2017

Niino, Hirai & Watanabe, 1987, as cited in Mahamood & Akinlabi, 2017
Basis of geometry generation

**Functionally Graded Materials**
- Exist in nature
- Have *gradually-changing porosity, microstructure or chemical composition* over the entire volume of the material
- The varying properties of the material *depend on the spatial position in the geometry*
- Resulting in *having particular functions and performance*

**Metamaterials**
- Do not exist naturally
- Primary concept: creating new materials by *designing microstructural units* and assembling them to obtain the target properties and performance.
- Physical properties *depend on the internal microstructures* of the material.
- Properties can be engineered by *altering the internal microstructures*

Miyamoto, Niino & Koizumi, 1997, as cited in Mahamood & Akinlabi, 2017
Niino, Hirai & Watanabe, 1987, as cited in Mahamood & Akinlabi, 2017
Engineered geometry

Based on the opportunities offered by FGMs and metamaterials, the target is to engineer the microstructure of the dynamic insulation to obtain the expected performance.
Engineered geometry

The geometries will be generated by designing their unit-cells.

Modifying the unit-cells results in the change of properties such as porosity, surface roughness, etc.

Gradual change of cavity volume occurs over time in response to the outside velocity.
Texture-based metamaterials

A specific type of metamaterials that are generated based on textures as primitive design elements.

Texture

“The quality of something that can be decided by touch; the degree to which something is rough or smooth, or soft or hard”

Cambridge English Dictionary
“Texture” in 3D sampling

“Gray-scale image of point cloud data whereby pixel brightness correlates to surface height at a given point”

Patel, Tam, et al., 2017
Sources of all textures are included in the appendix.
Parameters affecting air flow rate & pattern

**Geometry**
- Cavity volume
- Surface roughness
- The inlet to outlet ratio
- Reynolds number
- Angle of attack
- Location of the inlet
- Cross section of the passage
- Drag: Form and Friction
- Total length of the path
- Speed of response of the fluid microstructure

**Texture**
- Direction
- Intensity distribution
- Texture density
- Placement of the cropping
- Repetition of patterns

**Environmental conditions**
- Pressure gradient
- Velocity
Parameters affecting airflow rate & pattern

**Geometry**
- Cavity volume
- Surface roughness
- The inlet to outlet ratio
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- Location of the inlet
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- Repetition of patterns

**Environmental conditions**
- Pressure gradient
- Velocity
Digital workflow

Geometry generation

Start → Texture extraction → Texture sampling → Image processing → Synthesis

Conclusions → Further analysis of the selected geometry → Properties evaluation → CFD simulation

The relation between geometry and airflow rate/pattern
The relation between texture and airflow rate/pattern
Digital workflow: Geometry generation

UNIT-CELL

STACKED ASSEMBLY

Unit-cell generation in Grasshopper
Geometry variations based on different sample textures
EVALUATION
Digital workflow: Properties evaluation

Geometry
- Cavity volume
- Surface roughness
- The inlet to outlet ratio
- Reynolds number
- Angle of attack
- Location of the inlet
- Cross section of the passage
- Drag: Form and Friction
- Total length of the path
- Speed of response of the fluid microstructure

Texture
- Direction
- Intensity distribution
- Texture density
- Placement of the cropping
- Repetitive patterns

Environmental conditions
- Pressure gradient
- Velocity
Simulation tool: Ansys Fluent

Goal: simulating the flow of air inside a unit-cell
The simulated geometries in this section represent the **cavity in the unit-cell.**
Resembling the fluid-microstructure

Three defined scenarios

- **Low velocity**
  - Larger cavity volume
  - Main geometry
  - Time

- **High velocity**
  - Smaller cavity volume
  - Main geometry
  - Time

It has to be noted that there are more positions for each geometry and these three scenarios are just representatives of the fluidity of the structure.
Resembling the fluid microstructure

Small cavity volume  Initial state  Larger cavity volume

intersection area of the two layers in the unit cell
Geometry 1

Based on direction-less texture with radial distribution pattern
Expectation: Eddies and chaotic streamlines in the fluid domain.

Simulation results: Not chaotic streamlines

Nonetheless, it is possible that this might be different in geometries based on other direction-less textures
Variation A - Larger cavity volume

Smaller velocity range compared to the main geometry (almost one-third)
Variation B - Smaller cavity volume

Low velocity scenario

Highest normalized pressure-drop (0.98) among the variations of this geometry due to backflow and eddies in the cavity
Occurrence of eddies and backflows in the cavity
The larger the intersection area, the higher its impact on the streamlines.
Distinct high pressure-drops along the direction of the flow due to vertically-directed intersection areas which induce major form drags.

Lower pressure-drops along the horizontally-directed intersections areas due to smaller form drag
The influence of texture in this geometry was not discernible and cavity volume as a geometry-related factor had much higher impact on the pressure drop and the outlet velocity.

<table>
<thead>
<tr>
<th>Geometry 1</th>
<th>Larger cavity volume (G1-A)</th>
<th>Main geometry (G1)</th>
<th>Smaller cavity volume (G1-B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity volume (cm³)</td>
<td>949</td>
<td>898</td>
<td>823</td>
</tr>
<tr>
<td>Inlet to outlet ratio</td>
<td>1.01</td>
<td>1.45</td>
<td>1.09</td>
</tr>
<tr>
<td>Average inlet pressure (Pa)</td>
<td>6.43</td>
<td>38.61</td>
<td>1238.53</td>
</tr>
<tr>
<td>Average outlet pressure (Pa)</td>
<td>2.65</td>
<td>7.08</td>
<td>26</td>
</tr>
<tr>
<td>Normalized pressure drop (ΔP/P_inlet)</td>
<td>0.58</td>
<td>0.81</td>
<td>0.98</td>
</tr>
<tr>
<td>Inlet velocity (m/s)</td>
<td>2</td>
<td>2</td>
<td>3.5</td>
</tr>
<tr>
<td>Average outlet velocity (m/s)</td>
<td>2.07</td>
<td>3.16</td>
<td>5.1</td>
</tr>
</tbody>
</table>

The larger the normalized pressure-drop, the higher the outlet velocity.
The clear horizontal lines in the base texture distributed the flow lines almost evenly. In the geometry with vertical channels, the flow distribution was not uniform and the influence of the vertical channels was more significant at the bottom part of the geometry due to larger channel size. Also eddies occurred in some regions. Contrary to Geometry 3, the outlet velocity in Geometry 4 with horizontal channels (5.31 m/s) was higher compared to both its inlet velocity (2 m/s) and the outlet velocity of the geometry with vertical channels (2.63 m/s) (appendix K and L for comparison of the velocity contours).
Variation with horizontal channels

Velocity streamlines display a uniform distribution.
Variation with vertical channels

Change of the streamlines mostly occurred in the cross-sectional areas of the vertical channels, with eddies in some parts
As expected, the normalized pressure-drop in variation with the vertical channels is higher.
Variation B - Smaller cavity volume

Low velocity scenario
Velocity streamlines are primarily affected and distributed by the horizontal channels in the geometry.
Pressure contour is almost invariable, except in the area with the closed channel.
Further analysis
Geometry 4 with horizontal channels

With the increase of the inlet velocity, both the pressure drop and outlet velocity increases. The changes of both parameters as a function of the inlet velocity is not linear.
**Volume flow rate** changes with a constant rate of *almost two* while the changes of the **pressure drop do not follow a linear trend.**
Evaluating the effect of cavity volume on the pressure drop and outlet velocity

<table>
<thead>
<tr>
<th>Width (cm)</th>
<th>1.6</th>
<th>1.8</th>
<th>2</th>
<th>2.2</th>
<th>2.4</th>
<th>2.6</th>
<th>2.8</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average inlet pressure (Pa)</td>
<td>4.9</td>
<td>3.62</td>
<td>3.03</td>
<td>2.57</td>
<td>2.32</td>
<td>2.07</td>
<td>1.98</td>
<td>1.79</td>
</tr>
<tr>
<td>Average outlet pressure (Pa)</td>
<td>1.52</td>
<td>1.35</td>
<td>1.18</td>
<td>1.15</td>
<td>1.14</td>
<td>1.05</td>
<td>0.97</td>
<td>0.96</td>
</tr>
<tr>
<td>Pressure drop (Pa)</td>
<td>3.38</td>
<td>2.27</td>
<td>1.85</td>
<td>1.42</td>
<td>1.18</td>
<td>1.02</td>
<td>1.01</td>
<td>0.83</td>
</tr>
<tr>
<td>Normalized pressure drop</td>
<td>0.69</td>
<td>0.63</td>
<td>0.61</td>
<td>0.55</td>
<td>0.51</td>
<td>0.49</td>
<td>0.51</td>
<td>0.46</td>
</tr>
<tr>
<td>Inlet velocity (m/s)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Average outlet velocity (m/s)</td>
<td>1.46</td>
<td>1.39</td>
<td>1.35</td>
<td>1.31</td>
<td>1.28</td>
<td>1.25</td>
<td>1.23</td>
<td>1.21</td>
</tr>
</tbody>
</table>
Comparison of friction factors and Reynolds number for each simulated cavity
Customized Moody chart for the specific geometries of this thesis

Friction factor ($f_D$)

Relative roughness ($\frac{\varepsilon}{D}$)

Reynolds number

- $\frac{\varepsilon}{D} = 0.4$
- $\frac{\varepsilon}{D} = 0.5$
- $\frac{\varepsilon}{D} = 0.6$
- $\frac{\varepsilon}{D} = 0.7$
- $\frac{\varepsilon}{D} = 0.8$
- $\frac{\varepsilon}{D} = 0.9$
- $\frac{\varepsilon}{D} = 1.0$

Widths:
- 1.6
- 1.8
- 2
- 2.2
- 2.4
- 2.6
- 2.8
- 3
How can complex microscale geometries contribute to regulating the air flow rate and pattern inside dynamic insulation, using the potentials of additive manufacturing?
What are complex geometries? How can they be generated and how can their properties be evaluated?
Functional complexity

- Variable ventilation performance
- Adaptive cavity volume
- Fluid-microstructure
- A self-regulating system

Representing the fluid-microstructure by simulating multiple static scenarios
Adaptation of a unit-cell
Adaptation of a cavity
Functionally Graded Materials

Have gradually-changing porosity, microstructure or chemical composition over the entire volume of the material.

The varying properties of the material depend on the spatial position in the geometry.

Static geometry of the material.

Texture-based metamaterials

Gradually-changing cavity volume over time in response to the induced pressure by the outside velocity as the stimuli of the system.

The changing outside velocity is the determinant parameter of the variation of properties over time.

The variation of properties is offered by the fluid-microstructure.

Metamaterials

Primary concept: creating new materials by designing microstructural units and assembling them to obtain the target properties and performance.

Physical properties depend on the internal microstructures of the material.

Properties can be engineered by altering the internal microstructures.
Material complexity

- Engineering the material by designing its unit-cells
- Properties dependent on form and size of the cavity
- Geometry performing as an unconventional porous medium
Based on the availability of the literature focusing on dynamic insulation, it can be said that this topic is still evolving and has unknown areas which require investigation and research. Most research papers are based on the principles of this system and have tried to explore it with new components such as using different materials (concrete, wood, etc) or using water circuits to induce temperature change. However, they have only explored the system using geometries with simple circular pores. Therefore, it became evident that the use of complex geometries is not yet investigated. Since the proposed geometries have varying porosity over time, they can offer various functionalities in response to the outside air and have the potential to improve the performance of dynamic insulation compared to using static geometries.

**Why implementing complex geometries in the design of dynamic insulation could offer a potential contribution to the performance of the system?**

- Unknown areas in the current literature
- Most papers focused on the principles
- Use of complex geometries is not yet investigated
- Proposed geometries with varying cavity volume over time
- Different functionalities in response to the velocity
- Providing a variable ventilation performance
What is the effect of texture on air flow rate and pattern?

Characteristics of textures

- Texture density
- Placement of the cropping
- Repetition of patterns

Direction

Intensity distribution
What is the effect of texture on air flow rate and pattern?

- **Horizontal**
  - Unified streamlines, relatively low pressure-drops

- **Vertical**
  - Irregular streamlines, occurrence of eddies and backflows in the cavity, and high pressure-drops

- **Direction-less**
  - The influence of direction is not as much as the ones with a dominant direction
What is the effect of texture on air flow rate and pattern?

- **High**
  - Higher surface roughness and more irregular streamlines in the cavity

- **Low**
  - Smoother surfaces, relatively parallel streamlines with almost no eddies (depending on the width of the cavity)

Intensity distribution of the texture does not have a significant impact on the pressure drops in the designed geometries.
What is the effect of texture on air flow rate and pattern?

The effect of texture on air flow rate is inconclusive due to occurrence of eddies, and different inlet and outlet areas.

Yet, these results are the outcome of simulations on a limited group of selected geometries and textures.

Further simulations on a larger sample group is required to draw definite conclusions.
What is the effect of surface roughness on the air flow rate and pattern?

Surface roughness

Low \[\rightarrow\] High

Cavity width

Large \[\rightarrow\] Small

Eddies, backflows & turbulent streamlines
What is the effect of the geometry’s changing cavity volume and morphology of the air channels on the air flow rate and pattern?

Different cavity volumes result in different porosities of the geometry.
What is the effect of the geometry’s changing cavity volume and morphology of the air channels on the air flow rate and pattern?

- **Cavity volume**
  - **Small cavity volume**: Accelerates the air flow rate and results in eddies, backflows and high pressure-drops
  - **Large cavity volume**: Does not induce high pressure-drops, considerable change in the air flow rate or pattern
What is the effect of the geometry’s changing cavity volume and morphology of the air channels on the air flow rate and pattern?

Size of the cavity

Small cavity volume

Can be intensified by the base texture of the geometry.

Large cavity volume

Does not induce high pressure-drops, considerable change in the air flow rate or pattern
What is the effect of the geometry’s changing cavity volume and morphology of the air channels on the air flow rate and pattern?

- **Size of the cavity**
  - **Small cavity volume**
    - Texture with horizontal direction
      - Much less eddies, high pressure-drop due to the small cavity volume rather than the direction of the texture
    - Texture with vertical direction
      - High pressure drops, turbulent flow, eddies mostly in the areas with vertical channels
  - **Large cavity volume**
    - Does not induce high pressure-drops, considerable change in the air flow rate or pattern
What is the potential contribution of additive manufacturing to this process and research?

**4D printing**
Printing 3D objects that deform and reconfigure over time in response to an external stimuli

**Production of complex geometries with cavities**
An efficient technique to fabricate such geometries as using conventional technologies such as casting is impractical and costly.

**Using responsive materials**
Shape memory polymers: the inherent shape memory effect enables the reversible changes of the structure.

**Local fine-tuning**
- Locally adjusting the structure based on the performance or aesthetics requirements
- Using materials with different visual properties
Creating a digital workflow that integrates the design and evaluation phase, allowing for later optimizations

Calculating the required permeable area based on the required flow rate and allowed average velocity

Selection of a suitable manufacturing process and material

Local fine-tuning if required

Simulation of Fluid-Structure Interaction (FSI) as it would be in the real-life application

Printing the geometries

Next steps
Future vision

Developing a design toolkit based on a textures database
Thank you!
APPENDIX
**Direction of the translation of texture to geometry**

The pixel brightness of a point in the texture corresponds to the surface height of the given point in the geometry. When the texture is ready to be translated to a geometry, there are two options that can be taken to generate the geometry:

- White pixels represent mountains, black pixels represent valleys.
- White pixels represent valleys, black pixels represent mountains.

Therefore, depending on the direction of the translation of texture to geometry, the stacked assembly would be different.
Surface roughness and its effect on airflow
3D Sampling

3D Sampling is a novel robust method that provides the designer with a range of different alternatives to compare their properties.

Patel, Tam, et al., 2017

Textures from

https://steemit.com/nature/@lazariko12/is-wood-cutting-really-that-bad-for-nature
http://gigl.scs.carleton.ca/node/1162
https://www.pinterest.co.uk/pin/463659724127121520/
http://www.cbdpools.com/ceramics-close-up/ceramic-g1-tx-007/
https://www.shutterstock.com/image-photo/red-snake-skin-pattern-texture-background-300346820
https://www.pinterest.at/pin/512354895092725379/
https://i.pinimg.com/736x/4a/cd/cd4acd03882b26e35245fe2c4cab0064.jpg
https://www.gettyimages.no/detail/photo/close-up-view-of-zebra-stripes-royalty-free-image/170615172?adppopup=true
Geometry 2

Based on direction-less texture
No significant change in the velocity streamlines due to direction-less base texture

Non-uniform velocity contour at outlet with higher outlet velocity compared to the inlet
Variation A - Larger cavity volume

Smaller velocity range compared to the main geometry (almost one-third)
Variation B - Smaller cavity volume

Highest normalized pressure drop (0.87) among the variations of the geometry due to backflow and eddies in the cavity
Turbulent flow shows eddies and recirculation of streamlines in different areas.
Variation A and B had similar inlet to outlet ratios. However, the normalized pressure drop in variation B was almost double the pressure drop in variation A due to the eddies and backflows.

<table>
<thead>
<tr>
<th>Geometry 2</th>
<th>Higher porosity (G2-A)</th>
<th>Main geometry (G2)</th>
<th>Lower porosity (G2-B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity (φ)</td>
<td>0.60</td>
<td>0.59</td>
<td>0.57</td>
</tr>
<tr>
<td>Cavity volume (cm³)</td>
<td>953</td>
<td>926</td>
<td>898</td>
</tr>
<tr>
<td>Inlet to outlet ratio</td>
<td>0.99</td>
<td>1.07</td>
<td>0.97</td>
</tr>
<tr>
<td>Inlet pressure (Pa)</td>
<td>4.90</td>
<td>26.70</td>
<td>94.66</td>
</tr>
<tr>
<td>Outlet pressure (Pa)</td>
<td>2.52</td>
<td>4.31</td>
<td>11.68</td>
</tr>
<tr>
<td>Normalized pressure drop (ΔP/P_{inlet})</td>
<td>0.48</td>
<td>0.83</td>
<td>0.87</td>
</tr>
<tr>
<td>Inlet velocity (m/s)</td>
<td>2</td>
<td>2</td>
<td>3.5</td>
</tr>
<tr>
<td>Outlet velocity (m/s)</td>
<td>1.9</td>
<td>2.41</td>
<td>3.87</td>
</tr>
</tbody>
</table>

Similar to Geometry 1, cavity volume as a geometry-related factor had much higher impact on the pressure drop, compared to the influence of texture.