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Breathing walls: The design of porous materials for heat exchange and decentralized ventilation

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ABSTRACT

This study demonstrates how to design pores in building materials so that incoming fresh air can be efficiently tempered with low-grade heat while conduction losses are kept to a minimum. Any base material can be used in principle, so long as it can be manufactured with millimeter-scale air channels. The channel-pores are optimized according to the thermal conductivity of the base material, the dimensions of the panel, and the suction pressure sustained by a given fan or a chimney. A water circuit is integrated at the interior surface to ensure direct thermal contact and prevent radiant discomfort. Correlations from the thermal sciences literature were used to optimize the size and distribution of channel-pores in wood, glass, and concrete test panels. The measurements showed good agreement with theory and were presented in a general form so that designers can predict the steady-state performance of any optimal design in sensible heat-transfer mode. Schlieren imaging was used to characterize the different regimes of mixed convection at the interior and exterior surface. The data explain the discrepancy between prediction and measurement in the dynamic insulation literature, and how the integrated water circuit overcomes these problems. Surface heat-flux measurements were correlated in a general form so that designers can account for convection at the interior and exterior surface.

1. Introduction

Modern enclosures are designed as insulators and made from layers of different materials. But it might be better to design them as heat exchangers, using one base material that can perform several functions. This paper describes a method for designing building materials as heat exchangers, so that incoming fresh air can be efficiently tempered with low-grade heat while conduction losses are kept to a minimum (Fig. 1). Any base material can be used in principle, so long as it can be manufactured with millimeter-scale air channels.

The results of two experiments are reported. The first experiment measures the convection at the surface of a porous heated plate as air is sucked or blown through the pores. The results are correlated to characterize the different kinds of convection between a room and a porous wall. This is important because, in order to transfer heat to the air flowing through it, a porous material must first receive heat at one face. Precedents in the building science literature underestimate the importance and complexity of the first transfer stage.

The second experiment measures the heat exchange inside glass, concrete and wood samples designed with parallel channels. The results validate a materials design method from the thermal sciences literature, which can be used to design high-tech porous materials, such as turbine blades that are cooled through their pores to withstand extreme heat. Taken together, the results of our two experiments show how to translate that method to the context of building design, while resolving problems associated with *dynamic insulation*.

1.1. Dynamic insulation

In the 1960s, '70s, and '80s, engineers in Norway, Canada, Sweden, Denmark, Finland, and Switzerland developed a new ventilation system for livestock buildings, based on a novel idea for recovering heat [1]. A layer of porous insulation divided the shed into a room and an attic. The attic space extended half way down the walls to form a wrap-around cavity. With a fan, fresh air from the cavity was sucked into the room through the porous insula-

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Subscript

A	area [m^2]
c_p	specific heat capacity [J kg^{-1} K^{-1}]
D	diameter of channel [m]
H	height of unit (channel spacing) [m]
h	heat transfer coefficient [W m^{-2} K^{-1}]
k	thermal conductivity [W m^{-1} K^{-1}]
L	length of channel (depth of panel) [m]
T	temperature [K, °C]
Q	volumetric flow rate [m^3 s^{-1}]
q''	heat flux [W m^{-2}]
u	area-averaged velocity [m s^{-1}]
x	length/height at point of measurement [m]
α	thermal diffusivity [m^2 s^{-1}]
β	thermal expansion coefficient [K^{-1}]
ΔT	temperature difference [K, °C]
ΔP	pressure difference [Pa]
ΔZ	height difference
ϵ	Emissivity
ε	heat-exchange efficiency
μ	dynamic viscosity [kg s^{-1} m^{-1}]
ν	kinematic viscosity [m^2 s^{-1}]
ρ	density [kg m^3]
ϕ	void fraction (porosity)
Be	Bejan number
NTU	number of Transfer Units
Nu	Nusselt number
Pe	Péclet number
Pr	Prandtl number
Ra	Rayleigh number
Nu_m/Nu_n	ratio of mixed convection to natural convection
$\sqrt{Pe}/Nu_n$	ratio of forced convection to natural convection

Subscript

a	air
ae	air, exterior
ai	air, interior
c	convection
m	mixed (measured)
max	maximized
min	minimized
n	natural
opt	optimized
r	radiation
s	surface
se	surface, exterior
si	surface, interior
x	local, at point of measurement

tion. On its way through the pores, the fresh air was warmed by heat conducting out through the material in the opposite direction. The Norwegian phrase *Motstrømstak* highlighted the novelty of counter-current exchange [2], while, in German, *Porenlüftung* alluded to the idea of 'breathing' with ventilation through pores [3]. British researchers later settled on the term *dynamic insulation* [4].

In the 1980s, '90s, and '00s, engineers more carefully examined the heat-recovery traits of open-pore and fibrous materials [5,6], and worked on transferring the *dynamic insulation* concept from industrial cattle-sheds to homes [7], offices [8,9], and sports facilities [10]. The goal was to save energy while providing more than the minimum fresh air. However, while initial experiments showed good agreement with theory [1,4], later experiments gave inconclusive results and suggested some serious limitations. With increasing fresh air, the temperature of the interior surface tended to fall, and so, therefore, did the portion of recovered heat and the radiant temperature of the interior [7,11,12]. Researchers turned their attention to the air-filtration characteristics [13], before moving on to the study of heat-recovery concepts that do not use porous materials [14].

A new series of studies were conducted 2015 and 2016. Researchers examined micro-scale [15], latent [16], and transient [17] heat transfer; the filtration of particulates [18]; and the use of buoyancy to replace fans [19]; while one group developed custom apparatus to test some of these aspects in combination [20]. But despite the renewed interest, today's designs share two common features worth questioning. First, they presume to use stock insulation materials, so additional materials are needed to complete a given envelope design. Second, they incorporate an air-mixing cavity to cover the interior surface. However, this only seems to lessen the impact of the wayward surface temperature rather than resolve the issue conclusively.

This study revisits the basic premise of *dynamic insulation*, but takes a different approach, using a method from the thermal sciences literature [21]. The method shows how to optimize parallel channels in any material, to counteract exterior heating by forcing a coolant through the channels at a given pressure. Kim, Lorente, and Bejan [21] used analytical methods and numerical simulations to develop a set of design correlations that apply to a wide range of scenarios and base materials. Our experiment validates their results, which we present in standard notation for heat exchanger design, so they can be used to design building envelopes that exchange heat efficiently (rather than things like turbine blades for which hotspot temperatures are the primary concern).

1.2. Multifunctional materials

Technically speaking, *dynamic insulation* is a kind of heat exchanger. The laws of thermodynamics suggest a possible advantage to a heat exchanger enveloping a room: it might make it easier to exploit low-grade and renewable sources of heat. To achieve the same power from a larger exchange surface, one does not need an especially hot or cold control fluid—a tepid fluid will suffice [22,23].

Modern buildings are made up of many different materials and technologies, and it is rare for one member of the design team to have a complete picture of the functional interdependencies between all parts [24]. The process of design and construction is highly decentralized, and the activities, relationships, and conditions are often particular to the given project and site. General methods for materials design are needed, to show how concepts for multifunctional materials can be applied to any particular context, using local skills and materials, in a variety of ways.

Surveying the surfeit of bulk materials now available, some materials scientists advocate a method of combining existing materials with geometric features to create multifunctional hybrid materials [25,26]. Studying natural materials, some biologists argue we should improve the performance of simple constituent materials by manipulating their internal geometry at different length scales [27–29].

In a similar vein, Adrian Bejan and Sylvie Lorente propose an approach to materials design for cases where flows of heat, mass, and mechanical stress need reconciling. Based on the idea that natural and artificial systems reconfigure over time by adjusting to the currents that flow through them, *Constructal Theory* [30] has influenced a growing number of engineers worldwide. The methods have been used to design things such as heat exchangers, vascular materials, and transport networks, and to study natural flow systems such as lungs, rivers, and trees [31–34].