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Numerical investigation of energetic effects of flow-through wall elements

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ABSTRACT

The energy efficiency of buildings is of interest for both science and industry. In order to reduce the energy demand for heating and cooling, a new flow-through wall element is proposed allowing to switch the effective properties of the wall. By means of numerical modelling and simulation, the energetic effects of the wall element are studied for different cities (i.e. climatic conditions), flow speeds through the wall element, and volumetric heat capacities of the wall. Simulations at sufficiently small time steps for an entire year allow to determine the maximum heating and cooling loads, and the respective annual energies by integration. This reveals that the flow-through wall element is beneficial for most of the conditions and cities. For instance, it can be observed that the annual heating energy can be reduced to approximately half of those of a simple wall almost irrespective of the city. Contrary, the annual cooling energy reduction strongly depends upon the city and the flow speed. The primary energy analysis revealed a distinct minimum which is assigned to flow speeds of approximately $1\ \mathrm{m\ s^{-1}}$.

1. Introduction

The Paris agreement as the result of the United Nations framework convention on climate change forces the signing states to reduce their primary energy demand with its corresponding carbon dioxide emissions [1]. In order to meet the requirements, it is necessary to improve the energy efficiency of technical systems. The potential for savings is huge. For instance, heating and cooling processes require more than 65% and 14% of the energy demand in Germany, respectively [2]. A large number of studies of international teams support the necessity for energy efficiency research, see e.g. Refs. [3–11].

Earlier work considered especially the heating energy demand and its reduction by improved thermal insulation and air-tightness [12–15]. These efforts lead to the situation of massive over-heating especially in light-weight buildings during the summer period, when thermal loads cannot be rejected through the insulation. This yields a focus on the energy efficiency of *cooling generation*, a term which is not strictly physically correct, but a useful abbreviation for the process of *providing a heat sink with a temperature smaller than that of a particular zone in order to extract heat from there* (see e.g. Ref. [16] and references therein).

Extensive research has been carried out on the reduction of thermal loads by utilising materials which change their phase at some particular temperature. These so-called phase-change materials (PCM) provide a relatively high energy density, reducing therefore the peak loads [17–21]. Moreover, the utilisation of environmental energies driving a heat pump became popular as well, for instance geothermal energy [22–25] or heat from the air [26,27]. Multi-objective optimisations provided support for retrofitting design decisions considering, among others, the investments costs, net present value, and energy efficiency [28,29]. Herein, Malatji et al. [28] employed genetic algorithms, whilst Wu et al. [29] utilised the so-called multi-objective neighbourhood field optimisation. Lin et al. [30] investigated the rebound effect if the energy efficiency of buildings is improved. For instance, the authors observed that the rebound effect in rural residential buildings is larger than in urban areas in China.

Objective of this contribution is to reduce both the peak thermal loads and the primary energies of buildings by means of thermal activation of building components with a new flow-through wall element. Contrary to the ventilation system of Turnpenny et al. [31], where PCM stacks are included in the air-handling unit, a layer of air is used either for thermal insulation or activation of the wall. This principle is illustrated in Fig. 1. In order to suppress natural convection, the air is locked by channel separators. In some particular circumstances, the air is forced through the channels by a fan for activation purposes. Hereby, the channel is considered to be an open system. Although the method described here is generally valid, the subject under consideration is the building. It can be also employed for industrial applications were variable properties of housings are desired.

By means of numerical modelling and simulation, the thermal loads are calculated in a transient simulation for an entire year. From this data, the annual energies for heating, cooling, and operation of the wall element are determined and examined. The calculations are carried out for different varied parameters:

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Nomenclature

Latin symbols

a	Absorption coefficient, –
a	Coefficient of the discretised equation, –
c_p	Specific heat, $\mathrm{J\,kg^{-1}\,K^{-1}}$
D	Diffusive flux, $\mathrm{m\,s^{-1}}$
E	Energy density, $\mathrm{W\,m^{-2}}$
F	Convective flux, $\mathrm{m\,s^{-1}}$
h	Specific enthalpy, $\mathrm{J\,kg^{-1}}$
I	Irradiation density, $\mathrm{W\,m^{-2}}$
k	Thermal conductivity, $\mathrm{W\,m^{-1}\,K^{-1}}$
L	Length, m
$\boldsymbol{m}$	Material, –
$\boldsymbol{n}$	Normal vector, –
p	Pressure, $\mathrm{N\,m^{-2}}$
P	Power density, $\mathrm{W\,m^{-2}}$
$\dot{\boldsymbol{q}}$	Heat flux vector, $\mathrm{W\,m^{-2}}$
R_i	Specific gas constant, $\mathrm{J\,kg^{-1}K^{-1}}$
t	Time, s
T	Temperature, K
$\boldsymbol{u}$	Velocity vector: $\boldsymbol{u} = (u_x,\ u_y,\ u_z)^{\mathrm{T}}$, $\mathrm{m\,s^{-1}}$
$\dot{V}$	Air flow rate, $\mathrm{m^3\,s^{-1}}$
$\boldsymbol{x}$	Location vector: $\boldsymbol{x} = (x,\ y,\ z)^{\mathrm{T}}$, m

Greek symbols

α	Thermal diffusivity, $\mathrm{m^2\,s^{-1}}$
β	Relaxation factor, –
δi	Distance between two nodes of the mesh with $i \in \{x,\ y\}$, m
γ	Reynolds number ratio, –
ν	Kinematic viscosity, $\mathrm{m^2\,s^{-1}}$
ϱ	Density, $\mathrm{kg\,m^{-3}}$
ϕ	General quantity, –
ψ	Void fraction, –
σ_{S}	Stefan–Boltzmann constant: $\sigma_{\mathrm{S}} = 5.67\cdot 10^{-8}\,\mathrm{W\,m^{-2}K^{-4}}$
ζ	Friction factor, –
η_{op}	Energy efficiency factor for wall element operation, –

Non-dimensional numbers

Nu	Nusselt number: $Nu = hL_{\mathrm{ref}}\,k^{-1}$, –
Pe	Péclet number: $Pe = \langle u\rangle L_{\mathrm{ref}}\,\alpha^{-1}$, –
Pr	Prandtl number: $Pr = \nu\,\alpha^{-1}$, –
Re	Reynolds number: $Re = \langle u\rangle L_{\mathrm{ref}}\,\nu^{-1}$, –

Operators

l_2	l_2 norm of a vector
∇	Nabla operator: $\nabla = (\partial/\partial x,\ \partial/\partial y,\ \partial/\partial z)^{\mathrm{T}}$
Δ	Difference operator: $\Delta \neq \nabla^2$
∂_i	Partial derivative: $\partial_i = \partial/\partial i$ with $i \in \{t,\ x,\ y,\ z\ldots\}$
$\lvert\cdot\rvert$	Norm of a vector: e.g. $\lvert\boldsymbol{u}\rvert = (u_x^2 + u_y^2 + u_z^2)^{1/2}$
$\langle\cdot\rangle$	Volume-average of a quantity: e.g. $\langle T\rangle = L_x^{-1}\int T\,\mathrm{d}x$ or $\langle u_x\rangle = (\Delta y\Delta z)^{-1}\iint u_x\,\mathrm{d}y\,\mathrm{d}z$

Subscripts

a	Atmosphere
amb	Ambient
cond	Conduction
diff	Diffusive
dir	Direct
e	East cell face
E	East neighbouring node
eff	Effective
eq	Equivalent
g	Ground
int	Internal
lam	Laminar
lw	Long-wave (irradiation)
n	North cell face
N	North neighbouring node
op	Operation
rad	Irradiation
s	South cell face
S	South neighbouring node
ref	Reference
sw	Short-wave (irradiation)
turb	Turbulent
w	Wall
w	West cell face
W	West neighbouring node

Superscripts

T	Transposed (to be applied on tensors)
*	Non-dimensional quantity

- City (i.e. climatic conditions)
- Volumetric heat capacity ϱc_p of the wall
- Flow speed $\langle u_x\rangle$ if the wall element is switched on

2. Numerical model

2.1. General

The objective of the numerical model is to be both simple and precise enough to allow annual simulations. For the sake of simplicity, the extent of the computational domain is reduced as much as possible. Thus, thermal conduction is solved in two-dimensional space longitudinal (x-direction) and transversal (y-direction) to the fluid flow, employing periodicity conditions in z-direction. Despite the fact that real walls are usually composed of several layers, the wall is assumed to be of a single one here, for demonstration purposes. Utilisation of well-established heat transfer equations, rather than solving the full advection–diffusion problem in the fluid, allows a one-dimensional treatment of the heat transfer in the fluid. This step provides the most important reduction. The remaining numerical model is a completely physics-based discretised form of the transient energy partial differential equation and is therefore free of empirical parameter-fitting. Adjustments in the numerical scheme are employed for the sake of speed-up and stabilisation of the simulations not affecting the solution itself.

2.2. Mathematical model

The mathematical model is based on the transient energy equation neglecting viscous heating and pressure work ([32–35]):

$$\partial_t(\varrho h) + \nabla\cdot(\varrho\boldsymbol{u}h) = -\nabla\cdot\dot{\boldsymbol{q}}. \tag{1}$$

Herein, $\varrho = \varrho(\boldsymbol{x})$ is the density, $\boldsymbol{u} = \boldsymbol{u}(\boldsymbol{x})$ is the velocity vector, $h = h(\boldsymbol{x})$ is the specific enthalpy, $\dot{\boldsymbol{q}} = \dot{\boldsymbol{q}}(\boldsymbol{x})$ is the heat flux vector, $\boldsymbol{x} = (x,\ y,\ z)^{\mathrm{T}}$ is the location vector, $\partial_t = \partial/\partial t$ is the partial time derivative, and $\nabla = (\partial/\partial x,\ \partial/\partial y,\ \partial/\partial z)^{\mathrm{T}}$ is the Nabla operator.