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Numerical and experimental study of a solid matrix Electric Thermal Storage unit dedicated to environmentally friendly residential heating system

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ABSTRACT

This paper presents the concept of a sensible heat Electric Thermal Storage (ETS) system dedicated to household central heating. ETS is the technology of converting off-peak electricity into heat and using it in household heating 24 h a day. An ETS system is comprised of electric heating elements which are embedded within a high-density solid matrix. Since the thermal energy is stored in the solid matrix during off-peak hours and is discharged during peak hours, it results in significant savings in the household heating cost. A numerical model is developed to analyze the performance of the ETS unit, the central component of the presented system. The energy conservation equations for the solid matrix and air domains are formulated. Solid matrix is modeled as a porous medium, where radial heat conduction is neglected. The governing system of differential equations with boundary and initial conditions is solved using the Finite Volume Method. The developed model allows determining the air temperature at the outlet of the Electric Thermal Storage unit. Despite the simplified assumptions considered in the numerical model formulation, a good coincidence of the computation results with experimental data is reached. The heating system proposed in the paper meets the air quality requirements imposed by the environmental regulations and is an efficient and environmentally friendly heating systems for residential buildings.

1. Introduction

A considerable part of the European population lives in urban areas, where air pollution is often very high. The issue of significant air pollution concerns not only large agglomerations but also small cities and rural areas where air pollution is caused by incomplete combustion of bad quality solid fuels and domestic wastes. The air pollutants that significantly affects human health are particulate matter (PM) and Polycyclic Aromatic Hydrocarbons (PAH), among others [1–5].

Particulate matter and Polycyclic Aromatic Hydrocarbons are present in emissions from industry, traffic, domestic heating and agriculture. PM10, i.e. particles less than 10 μm in diameter that are suspended in the air, can cause asthma, cardiovascular problems, lung cancer and premature deaths which exceed the number of yearly deaths by road traffic accidents [3,6]. EU (European Union) legislation on ambient air quality and cleaner air for Europe [2] sets a limit values for PM10 exposure covering both an annual concentration value (40 $\mu g/m^3$) and a daily concentration value (50 $\mu g/m^3$) that must not be exceeded more than 35 times in a calendar year.

Due to their carcinogenic and mutagenic character, PAHs are considered as the most dangerous air pollutants [4]. PAHs emitted from combustion or other high-temperature sources (e.g. benzo(a)pyrene – BaP) are typically associated with the particulate matter of small size (<1.0 μm) [5]. Ambient air concentrations of BaP are high in vast areas of Europe, mostly due to emission from the domestic combustion of fossil fuels and wood, contributing up to 82% (2012) of the total BaP emissions [4]. More than 30% BaP

Abbreviations: BaP, benzo(a)pyrene; PAH, polycyclic aromatic hydrocarbons; BITES, buildings integrated TES; PCM, phase change material; EU, European Union; PM, particulate matter; ETS, Electric Thermal Storage; PV, photovoltaic; FEM, finite element method; RES, renewable energy sources; FVM, finite volume method; RMSE, root mean squared error; HVAC, heating ventilating and air conditioning; TES, thermal energy storage; MAPE, mean absolute percentage error.

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Nomenclature

A Area, m^2
A_{ETS} Cross−sectional area of the ETS unit, m^2
Bi Biot number, -
c Specific heat, J/(kg K)
c_p Specific heat at constant pressure, J/(kg K)
D_{int} Inner diameter of the steel tube, m
D_{ex} Outer diameter of the ETS unit shell, m
D_{out} Outer diameter of the steel tube, m
D_{sh} Inner diameter of the ETS unit shell, m
d_c Diameter of the ceramic cylinders, m
h_f Effective heat transfer coefficient, W/(m^2 K)
i Node number in a finite difference grid
k Thermal conductivity, W/(m K)
L Length of the ETS unit, m
$\dot{m}$ Mass flow rate, kg/s
m Number of ceramic elements rows placed in a single steel tube, -
m_{st} Total weight of the steel tubes, kg
m_c Total weight of the ceramic cylinders, kg
N Number of ceramic cylinders in one row, -
N_f Number of heat transfer units for the air, -
N_t Total number of time-steps, -
n Time-step number, -
p Number of steel tubes inside the ETS unit, -
Q Quantity of heat, J
$\dot{Q}$ Heat flow rate, W
T Temperature, °C
$\hat{T}$ Experimental value of temperature, °C
t Time, s
V Volume, m^3
z Space coordinate, m
z^+ Dimensionless spatial step, -

Greek symbols
ρ Density, kg/m^3
φ Porosity, -
τ Time constant, s

Subscripts
0 Initial
c Ceramic
f Air
in Inlet
m Solid matrix
out Outlet
st Steel
w Water

Appendix A
h_c Heat transfer coefficient at the lateral surface of the ceramic cylinders, W/(m^2 K)
$h_{t,int}$ Heat transfer coefficient at the inner surface of the steel tube, W/(m^2 K)
$h_{t,out}$ Heat transfer coefficient at the outer surface of the steel tube, W/(m^2 K)
$h_{s,int}$ Heat transfer coefficient at the inner surface of the outer shell, W/(m^2 K)
p Pressure, Pa
$\mathbf{q}$ Heat flux vector, W/m^3
r Radius, m
$U_{s,out}$ Overall heat transfer coefficient for the outer shell insulation, W/(m^2 K)
w Mass average velocity, m/s
$\mathbf{w}$ Velocity vector

Greek symbols
$\boldsymbol{\tau}$ Viscous momentum flux tensor

Subscripts
fc Air flowing inside the inner tube
fs Air flowing in the space between the steel tubes and the outer shell
s Outer shell
t Inner tube
r Radial coordinate
z Axial coordinate
θ Angle in cylindrical coordinates

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monitoring stations across the Europe indicate exceedances in the concentration of BaP target value (1.0 ng/m^3), mostly in urban and suburban areas.

European countries located in the Central and Eastern Europe are affected by several phases of anthropogenic emissions of pollutants and drastic changes in air quality, particularly during the winter period. As it is shown in Fig. 1, all of the top ten most polluted cities in Europe in 2011 were located in Poland and Bulgaria. For instance, in the last five years, the daily limit values for the airborne particles PM10 have been persistently exceeded in 35 out of 46 air quality zones across the Polish territory [3]. The City of Cracow that is located in southern Poland experiences 150.5 days above the EU target levels of air pollution each year [6].