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ScienceDirect
Building and Environment 42 (2007) 3241–3252
BUILDING AND ENVIRONMENT
www.elsevier.com/locate/buildenv

Preliminary study of the performance and operating characteristics of a mop-fan air cleaning system for buildings

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Received 12 June 2006; received in revised form 6 July 2006; accepted 31 July 2006

Abstract

A theoretical investigation has been made into the performance of a novel mop-fan air cleaning system able to perform self-cleaning while circulating indoor air throughout the building space. The mop fan therefore reduces the need for outdoor fresh air and so energy for heating/cooling the air. The fluid dynamic characteristics of the mop impellers have been simulated using a model developed on the basis of previous test data. Characteristic parameters such as volume flow coefficient C_Q, pressure coefficient $C_{\Delta p}$ and power coefficient C_P, are indicated as the functions of rotation speed, mop fibre number and diameter. An optimum working state is recommended for maximum static efficiency. The UV light-photon characteristics of the mop cleaning system have been simulated using a model developed on the radial-diffusion assumption, and the photochemical reaction in the system has been investigated using Langmuir–Hinshelwood kinetic theory. A room self-cleaning process has been analysed, taking into account the effect of pollutant-generating rate and air flow rate on mop reaction efficiency and self-cleaning time. It is concluded that increased mop fibre diameter and quantity, as well as enhanced light source intensity, benefit the dynamic and photochemical performance of the mop cleaning system. Increasing the air flow rate and reducing pollutant-generating rate can significantly shorten the time to achieve a steady-state condition and helps to reduce pollutant concentration in the room.

Keywords: Mop; Reaction; Impeller; Photocatalyst; Light photon; Cleaning

1. Introduction

The UK government is committed to reducing carbon dioxide (CO_2) emission by 20% by the year 2010. The building sector accounts for about 50% of the total energy consumption of the UK and therefore a large proportion of its CO_2 emissions. Furthermore, the building sector is recognised as an area where significant reduction in emissions could be made. One way to reduce emissions would be to use lower ventilation rates and thereby reduce the amount of energy required for space heating/cooling and driving fans (in the case of mechanical ventilation). However, it is of course necessary to simultaneously provide adequate air quality and thermal comfort for building occupants. The difficulty of finding an acceptable solution to this problem has recently been demonstrated by the rejection of proposed ventilation standards (European prENV 1752 and its American equivalent), regarding air quality requirements, because the ramifications of increased energy consumption were considered to be unacceptable.

In some buildings, fresh air supply rates are set to dilute and remove pollutants which are hazardous to health (rather than simply being odorous). This is particularly true of buildings which house manufacturing processes. However, in any building there are inherent sources of volatile pollutants such as paint, furniture, carpets and office equipment. Effective removal of pollutants from indoor air would allow increased air recirculation reducing the need to introduce outdoor fresh air and so reduce the energy required to heat or cool this air. The proposed mop-fan air cleaning system meets this requirement, as it is able to perform self-cleaning while circulating indoor air throughout the building space.

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doi:10.1016/j.buildenv.2006.07.038

Nomenclature

a_s	area of TiO_2 surface, m^2
C	substrate quantity at the outlet of the mop reactor, ppm
C_0	substrate quantity at the inlet of the mop reactor, ppm
C_v	room pollutant concentration, ppm/m^3
C_Q	volume flow coefficient
$C_{\Delta p}$	pressure coefficient
C_P	power coefficient
D	mop impeller diameter, m
dV_r	differential volume of the space where air-pollutants mixture stayed, m^3
G_c	room pollutant-generating rate, ppm/s
I	UV light intensity on the surface of the TiO_2, W/m^2
k	the reactant concentration on the surface of the catalyst, ppm/m^2
K	the adsorption equilibrium constant
L	distance of the set point to the centre line of the UV lamp
N	motor rotation speed, rpm
n	number of mop fibre
P	input fan power, W
Q	air flow rate, m^3/s
R	UV lamp radius, m
r_c	the rate of disappearance of the substrate, ppm/s
V	room space volume, m^3
W	light power, W
W_l	light source power, W
t_0	stagnant time the substrate staying at the mop reactor, s
t	time, s
ϕ	mop fibre diameter, mm
Δp	static pressure of the mop fan, Pa
ρ	air density, kg/m^3
φ	quantum efficiency
η_m	mop reaction efficiency, %

2. Description of the mop-fan air cleaning system

The mop-fan air cleaning system is shown schematically in Fig. 1. The system comprises a flexible fibre mop, a UV lamp (UVA or germicidal UVC) positioned at the centre of the mop, a centrifugal fan casing, a motor and a shaft between the fibre mop and the motor. The flexible fibre mop, similar in appearance to a chimney sweep brush, is made of polymer fibres, each coated with a photocatalyst, namely, titanium dioxide. A shaft fitted within a centrifugal fan casing provides a direct link between the fibre mop and the motor, thus forming a compact unit. By this arrangement, the flexible fibre mop acts as an air impeller as well as a filter for removal of particulate pollutants [1]. In operation, the air being moved by the mop passes over the large surface area of the flexible fibres, which are bathed in ultraviolet light provided by a UV lamp (UVA or germicidal UVC). The titanium dioxide coating on the fibres is activated by the UV radiation and chemically oxidises volatile organic pollutants, converting them primarily to CO_2 and water [2]. This process of photocatalytic oxidation (PCO) destroys gaseous pollutants using highly powerful hydroxyl radicals produced by the irradiation of a semiconductor oxide (usually TiO_2) and UVA photons in the presence of oxygen and trace water vapour. PCO is highly effective for the destruction of a broad range of organic air pollutants [3–5] including, alkanes, alcohols, ketones, aromatics, organic acids, heteroatoms organics and halogenates, as well as inorganic pollutants [6]. Air-borne moulds, spores, bacteria and viruses can also been deactivated [7]. The internal surface of the fan casing is coated with a highly reflective material to spread the light evenly over the mop, and is finished with a layer of TiO_2 to achieve self-cleaning, similar to coating a glazing panel or mirror.

3. Fluid dynamic characteristics of the mop impellers

Testing on 11 types of mop impellers was carried out by the authors based on a standard method BS848 [8]. The geometric/motor parameters of the tested units are given in Table 1. The data obtained were used to assist the development of a fluid dynamic model, which indicates the characteristic parameters, i.e., air flow rate, pressure and efficiency, as functions of rotation speed, mop fibre number and diameter.

3.1. Mop air flow rate against motor rotation speed

A 0.37 kW, 1.15 A, 3 Phase Brook Crompton motor was used to drive the mop impellers [9]. Tests showed that increasing resistance at the outlet of fan unit resulted in a decrease in the air flow rate and an increase in motor speed. The measurement data are presented in Fig. 2, and a linear trend line indicating the variation of air flow rate against motor speed has been obtained. The error-squared of the line is 0.8785.

3.2. Optimum working state of the mop impellers

The static efficiencies of the mop impellers were measured and their variation in terms of air flow rate are indicated in Figs. 3 and 4. For any mop fibre diameter and quantity, the static efficiency achieved its maximum value when the air flow rate was at a certain level, i.e., around 0.12 m^3/s. This corresponded to a fixed motor speed of 1420 rpm. The point where the maximum static efficiency occurs is termed as the optimum working state, and the subsequent analyses refer to this specific state.