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Study for flow and mass transfer in toilet bowl by using toilet seat adopting odor/bacteria suction feature

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ABSTRACT

Recently, concerns for the indoor environment have significantly increased due to demands for a better quality of life. The bathroom has the poorest air quality in a building; nevertheless, it usually requires the best cleanliness. Most contamination sources in a bathroom are the unpleasant odor and bacteria due to feces. Instead of an air ventilation system that circulates all of the bathroom air, authors investigate numerically and experimentally a system that entrains the source from a toilet bowl and blocks the source's outflow. The system is simply installed inside the toilet seat. The effects of the suction flow rate, the suction hole size, and the number of suction holes are tested. The flow and concentration in the toilet bowl are numerically visualized. In addition, experimental results are in good agreement with the numerical results. Finally, the best conditions, a combination of the suction hole size of $4 \times 4\ \mathrm{mm}^2$ and rear two pairs open are obtained.

1. Introduction

Indoor air quality is important because people today spend approximately 90% of their time indoors. Many studies have shown that indoor air is of poorer quality than outdoor air [1–3]. Indoor air can deteriorate due to many causes such as dust (mites), tobacco smoke, and microorganisms. Countries have established requirements for indoor air quality [4–6]. Below 500 CFU/m^3 is a general guideline for bacteria or fungi (CFU is an abbreviation for "colony-forming unit," which is a measure of viable bacterial numbers). Microorganisms can be aerosolized out of toilets in bathrooms and grow by high humidity in bedrooms or living rooms. Jain [7] verified that over 40 fungal types prevail in organic matter-rich indoor environments such as food grain warehouses, library buildings, and bakeries. The indoor air quality (IAQ) in 64 elementary and middle school classrooms in Michigan was monitored by Godwin et al. [8]. The average indoor bioaerosol concentrations at elementary and middle schools were 1168–6661 CFU/m^3. These were far higher values than the recent regulation of 500 CFU/m^3. Five mold genera were found in schools, of which *Aspergillys/Penicillium* was by far the most common. Karbowska-Berent et al. [9] conducted a quantitative and qualitative study of the culturable fungi and bacteria in the air and settled dust in the storerooms of five Polish libraries and archives. In all studied storerooms, the total bioaerosol concentrations ranged from 100 to 1000 CFU/m^3. In addition, there is research to quantify microbial contamination on kitchen and bathroom surfaces in rural Cambodian homes, and the results were compared to similar data from the United States and Japan by Sinclair et al. [10]. According to their study, fecal coliform levels in Cambodia were highest in moist locations such as the plastic ladles used for sink water, toilet seat surfaces, and cutting board surfaces, with 100-fold higher levels of *Escherichia coli* and faecal coliform bacteria than has been reported in the US and Japanese studies. Their results emphasized the importance of increasing household environmental sanitation barriers.

Researchers have considered that fecal bacteria could contaminate the bathroom environment [11–17]. Best et al. [18] revealed the importance of toilet lids. They performed in-situ testing using faecal suspensions of *Clostridium difficile* (*C. difficile*) to simulate the bacterial burden found during disease, to measure *C. difficile* aerosolization. They verified that *C. difficile* aerosolization was discovered by air sampling at up to 250 mm above the toilet seat. In addition, the amount of detected *C. difficile* was maximized immediately after flushing. Consequentially, the floor was also contaminated with *C. difficile*. The lid must be closed to minimize contamination of the bathroom environment. What about the moment of defecation? Best et al. [18] showed that the bacteria

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continuously rise, which may lead to a disease of the anus. In addition, people have to keep smelling unpleasant odors.

Many researchers have studied the state of indoor air contamination or its sources during the last few decades. Also, numerous practical studies have been conducted to eliminate unwanted odor and bacteria in bathrooms. Most methodologies focused on how to design ventilation systems in bathrooms effectively so that the unwanted materials would not contaminate rooms. Chung et al. [11] simulated the airflow numerically and the flow path of contaminant particles in the bathroom with floor exhaust ventilation. Tung et al. [12] conducted an experimental study in a mock-up bathroom with a typical ceiling ventilation system. They utilized Sulfur hexafluoride (SF6) trace gas to verify the concentration at each sampling point. Their results showed that the removal efficiency of odors became more effective with higher ventilation rates and shorter distances between the toilet and the exhaust air vent, which reflects common sense. These two studies ([11] [12]) did not suggest an ultimate methodology for people to be safe from unwanted odor and bacteria.

In this study, a novel method was investigated and characterized to prevent unwanted sources such as odor and bacteria from coming out of toilets. The ultimate goal of our research is to extract all unwanted odors and bacteria into a suction system, and also to remove them using a novel filter that consists of an ionizer and catalyst materials. In order to extract the unwanted materials, a suction system inside a toilet seat was devised. The system is designed to suck material from the bottom of the seat. Numerical simulation was conducted to predict the air flow and the tracer gas concentration both inside and outside of the toilet bowl. Numerous cases were tested to examine a variety of suction flow rates, the number of suction holes, and sizes of suction holes. An actual suction system was fabricated for the validation of the numerical results. SF6 gas was used as a tracer gas.

2. Numerical analysis

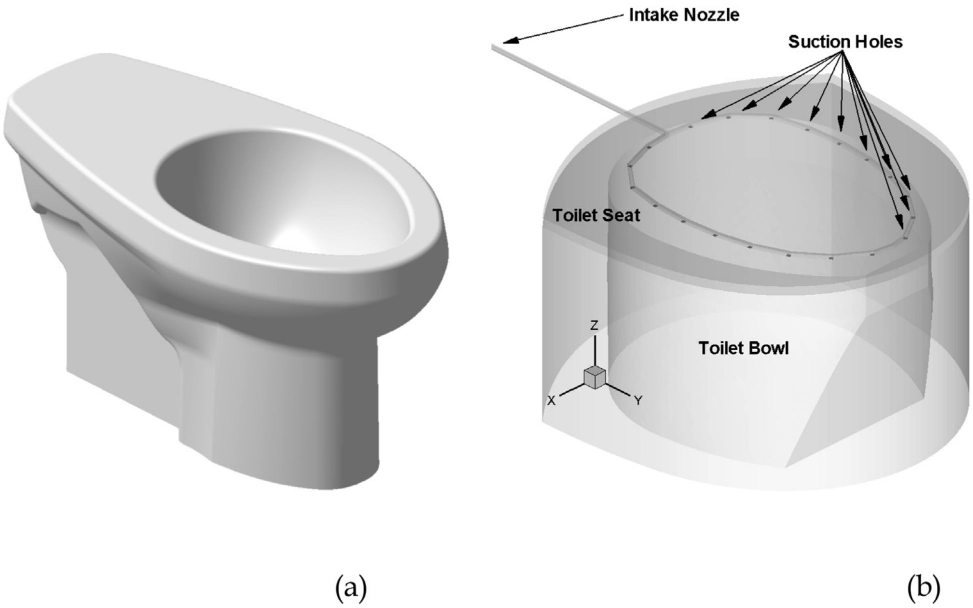
For the proposed system, authors simulated the performance of sucking odor and bacteria, or blocking their outflows, using numerical and experimental studies. Fig. 1 shows the shape of toilet bowl. The toilet bowl used in this study is a conventional and medium-sized bowl. Fig. 1(a) shows a three-dimensional CAD image for the real toilet bowl. Fig. 1(b) represents a simplified toilet bowl shape describing the inner surface of the real toilet bowl shown in Fig. 1(a). As shown in the figures, the toilet bowl is symmetric with respect to a meridian plane. The suction system and its induced air flowing structures are also symmetric with respect to the same plane. Thus, only one half of the domain with respect to the meridian plane was considered in this study.

Fig. 2 shows the odor suction system applied in this study. The system was designed to be installed inside the toilet seat, as shown in the figure. Twenty suction holes are evenly placed along the inner edge on the seat's bottom face. Each tip was connected to the same header tube, and a suction fan was set up at the other end of the header. Authors tested the air flow around the toilet bowl for different suction hole sizes and suction flow rates.

The total calculation domain around the toilet bowl is shown in Fig. 3. The outer surface of the cylindrical domain is 500 mm from the center of the toilet bowl. To evaluate system performance, authors used the odor concentration at a center point on the toilet bowl's top surface. The outside of the domain is regarded to be sufficiently large to apply a pressure outlet boundary condition; that is, the momentum at the boundary is simply extrapolated using the values for the inside neighboring cells. If inflows are detected at that boundary the concentration at the boundary is set to a constant value. Otherwise, if there are no inflows, the boundary concentration is extrapolated using the inside values for concentration. Two or three orders of magnitude lower concentrations are detected at that boundary, compared to the concentrations in the toilet bowl. A small inaccuracy so far from the toilet bowl could not significantly affect the results inside the toilet bowl.

To calculate the flow and odor transport for a three-dimensional, steady state, incompressible, and laminar flow field, the conservation equations of mass, momentum, and concentration can be written as:

$$\frac{\partial u_i}{\partial x_i} = 0 \qquad (1)$$



(a) (b)

Fig. 1. Configurations of toilet bowl.