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Design of an Inhalation Chamber to Expose Laboratory Animals with Suspended Particulate Matter Using Numerical Simulation Method

Hassan Rajabi-Vardanjani[1], Hassan Asilian-Mahabadi[1,*], Morteza Bayareh[2], Morteza Sedehi[3]

[1] *Department of Occupational Health Engineering, Faculty of Medical Sciences, Tarbiat Modares University, Tehran, Iran.*
[2] *Department of Mechanical Engineering, Faculty of Engineering, Shahrekord University, Shahrekord, Iran.*
[3] *Department of Epidemiology and Biostatistics, School of Public Health, Shahrekord University of Medical Sciences, Shahrekord, Iran.*

Abstract

Introduction: In toxicological studies of particulate matter (PM), inhalation exposure chambers (IEC) are usually used for distributing the test atmosphere uniformly and stability in the respiratory zone of laboratory animals. This study was aimed to design, evaluate and optimize a whole-body IEC, to expose small laboratory animals with PM.

Material and Methods: The initial design of the chamber was determined based on the advantages and disadvantages of the existing chambers. To create a uniform distribution of particles, metal guide plates were used in the upper cone. ANSYS Fluent software was used for numerical simulation and optimize the initial design. The used particles had a mean aerodynamic diameter of 10 microns. Particle concentration was measured along the cylindrical radius at 10 cm intervals on the x-axis. Then the percentage of variation coefficient (CV%) of the particle concentration for each line was calculated. The design with the lowest CV% was selected as the best chamber design.

Results: The optimized design has a cylinder section with two upper and lower cones, and two guide plates and its CV equal to 4.08%.

Conclusion: The optimized design was provided with a uniform and stable distribution of the particles to expose small laboratory animals.

Key words: Exposure chamber, Numerical simulation, Particulate matters, Inhalation exposure.

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*Corresponding Author : Hassan Asilian-Mahabadi
Email: Asilia_h@modares.ac.ir

1. Introduction

Air pollution in the gaseous and particulate phases has the potential to cause various diseases such as lung, cardiovascular and cancer diseases over the long term [1-4]. Researchers have developed and designed various chambers and exposure systems to evaluate the biological effects of airborne respiratory pollutants. These chambers were designed to provide uniform and stable distribution of the test atmosphere in the respiratory zone of laboratory animals [5]. The present study was aimed to design, evaluate, and optimize a whole-body exposure chamber, specifically for the exposure of small laboratory animals to inhalable particulate matter.

2. Material and Methods

In the first step, papers and scientific resources which had provided the technical details and performance of the inhalation exposure chambers were studied, and the advantages, disadvantages and those factors affecting their performance were extracted. Then the assumptions of the initial design of the chamber were prepared concerning the principles of fluid dynamics and the standard conditions of lab animal housing. To create a uniform distribution of particles inside the chamber, guide plates of flow were used in the upper cone. The inhalation exposure chamber was designed dynamic, whole-body, and specially designed for small laboratory animals. The chamber has a capacity for exposure to a maximum of 6 rats of 400 g, with an animal load of less than 5% of the total chamber volume [5]. To provide a uniform two-phase, gas-solid flow distribution in the chamber exposure section, the upper cone (inlet) angle of 45 ° and the lower cone (outlet) were designed with an angle of 60°. To prevent the flow from channeling (from the inlet to the outlet of the chamber), flow guides (full and partial cones) were installed in different coordinates and sizes (inside the upper chamber cone). Using numerical simulation, the effect of these plates on distributing particles at different levels of the chamber was investigated. In this study, copper inert particles with a mean physical diameter of 4 microns and mass distribution as normal logarithms were used. The chamber ventilation rate was considered 12 times per hour. The Velocity of inlet flow was calculated based on flow rate and inlet cross-sectional area. A steady-state, the governing equations on the flow of inhalation exposure chambers are continuity and momentum. Because of the existence of guide plates, the air flow in this is turbulent. The κ-ε perturbation model was used to model the turbulence of the flow and the discrete phase model (DPM) was used to simulate and trace the particles. Design Modeler, ANSYS Meshing, and ANSYS Fluent software were used to draw the geometries, meshing, and numerical simulations, respectively [6]. Experimental values of Chen’s study were used to validate the presumption numerical model [7]. After numerical simulation of the designs, particle concentration was sampled on the inner surfaces of the chamber at 10 cm intervals and the coefficient of variation of particle concentration at these levels was calculated. The best level was selected based on the lowest coefficient of variation and finally, the best design was selected.

3. Results

The optimized inhalation exposure chamber in the current study is of dynamic type and has a cylindrical section with two upper and lower cones (Figure 1). The flow from the upper section enters the chamber and after passing through the guide plates (Inner and middle cones) is distributed in the cylindrical part, then exits from the lower part of the chamber. The k-ε turbulence model was used to model the flow, and the discrete phase model (DPM) was used to simulate the particle distribution within the chamber and for the validation of the numerical model, the simulation results were compared with the experimental data of the reference paper (Figure 2). Among the 24 designs studied (Table 1), the lowest coefficient of variation of particle concentration was 4.08%. Properties of the optimized inhalation exposure chamber design were presented in Table 2.

4. Conclusion

Consideration of fluid dynamics principles in the design of inhalation exposure chambers of suspended particulates to provide the same exposure concentration is one of the necessities of designing such chambers [8]. In the current study, the numerical simulation method used to design and optimize the chamber and was able to provide comprehensive information on the field at

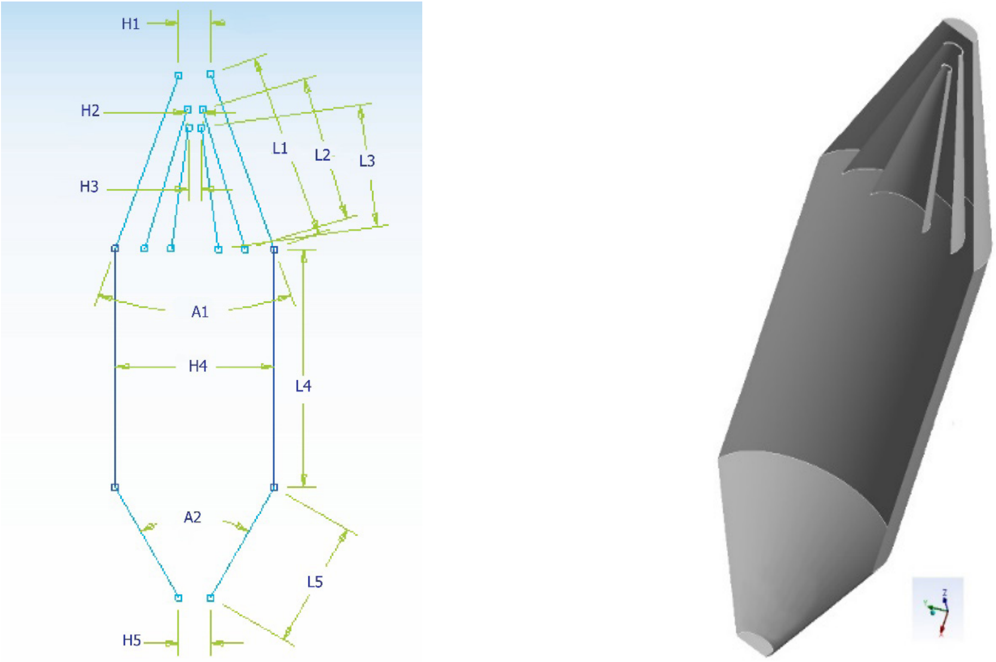

Fig. 1. Initial design of inhalation exposure chamber

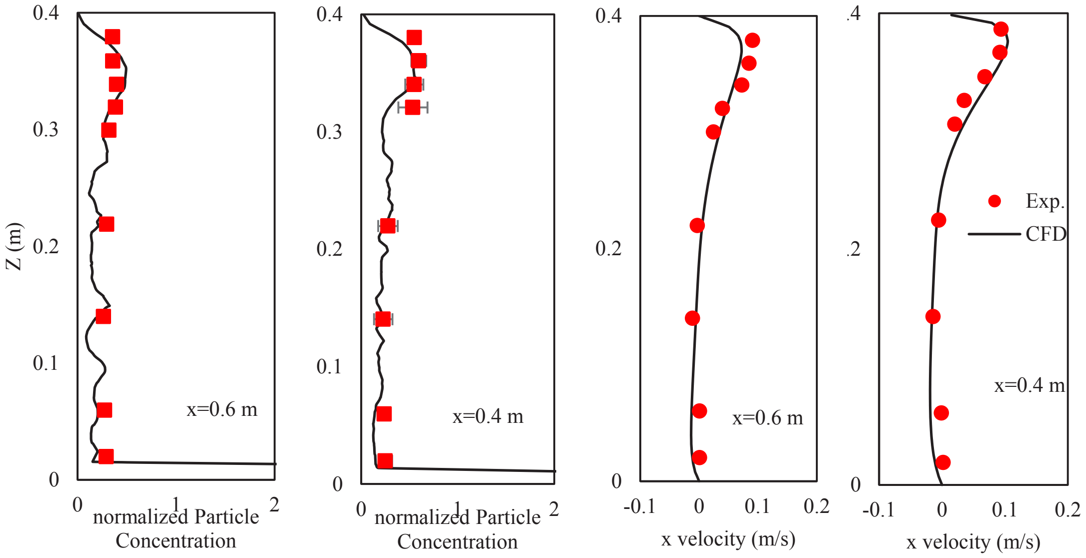

Fig. 2. variations of x component velocity and normalized concentration of the particles along the lines x = 0.4 and x = 0.6

a much lower cost than the experimental methods. The analysis of these data led to the selection of the best chamber design to provide uniform and stable concentrations of test particles in the animal respiratory area. The introduced chamber is applicable to the exposure of small laboratory animals to inert suspended particles.

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Table 1. Geometrical properties and dimensions of simulated chamber designs and associated response variables

Cod	Inner cone				Middle cone				Response variable	
	[c]DIO (cm)	L3 (cm)	H3 (cm)	Apex angle (degree)	[c]DIO (cm)	L2 (cm)	H2 (cm)	Apex angle (degree)	[b]OSDI (cm)	[a]CV%
1	No cone	-	-	-	No cone	-	-	-	120	5.9
2	10.8	42.02	1.35	10.5	5.4	49.5	2.7	19.1	130	45.87
3	10.8	24.37	1.35	10.5	5.4	31.1	2.7	19.1	50	19.82
4	10.8	6.7	1.35	10.5	5.4	12.68	2.7	19.1	120	6.18
5	10.8	6.7	1.35	16	5.4	12.68	2.7	24	100	6.32
6	10.8	6.7	1.35	10.5	5.4	12.68	2.7	24	100	7.65
7	10.8	6.7	1.35	16	5.4	12.68	2.7	19.1	90	4.08
8	10.8	6.7	1.35	10.5	5.4	18.62	2.7	19.1	60	10.22
9	10.8	12.4	1.35	10.5	5.4	18.62	2.7	19.1	70	6.74
10	10.8	12.4	1.35	10.5	5.4	12.68	2.7	19.1	120	5.46
11	16.2	6.7	1.35	10.5	10.8	12.68	2.7	19.1	80	8.05
12	16.2	11.8	1.35	10.5	10.8	12.68	2.7	19.1	100	5.38
13	10.8	6.7	2.7	10.5	5.4	12.68	2.7	19.1	120	6.5
14	10.8	24.37	1.8	10.5	5.4	31.1	3.6	19.1	110	4.58
15	10.8	24.37	1.35	10.5	5.4	31.1	3.6	19.1	130	9.5
16	No cone	-	-	-	5.4	48	2.7	13	110	31.8
17	10.8	16.65	1.35	10.5	No cone	-	-	-	130	34.5
18	10.8	42.04	1.35	10.5	No cone	-	-	-	60	36.3
19	No cone	-	-	-	5.4	49.5	2.7	19.1	130	36.6
20	No cone	-	-	-	5.4	50.4	0	22	130	79.49
21	10.8	42.28	0	22.7	No cone	-	-	-	130	50.4
22	21.6	35.54	0	30.4	No cone	-	-	-	120	75.4
23	10.8	12.05	1.35	16	5.4	17.97	2.7	19.1	80	6.60
24	10.8	1.65	1.35	16	5.4	7.39	2.7	19.1	90	6.12

*L2, L3, H2 and H3 Are presented in Figure 1.

[a] CV%=CV% of Particle Concentration on Selected Surface

[b] Optimal surface distance from input (OSDI)

[c] Distance to inlet opening (DIO)

Table 2. Properties of the optimized inhalation exposure chamber design

The main parts of the chamber	Slant height (cm)	Inlet cross-section radius (cm)	Outlet cross-section radius (cm)	Central angle	Installation coordinates* (cm)
Upper cone	56,44	5,4	27	45	(0, 0, 0)
Lower cone	43,2	27	5,4	60	
Middle cone	12,68	2,7	18	19,1	(5,4, 0, 0)
Inner cone	6,7	1,35	9	16	(10,8, 0, 0)

* Installation coordinates relative to the center of the inlet surface

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