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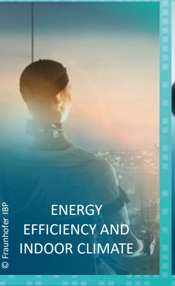
Concepts of air purification efficiency tests under realistic conditions with continuous bioaerosol source and evaluation of test results

Workshop
"Indoor Environmental Quality in Sustainable Buildings"
Stuttgart, 02 April 2025



Building on Knowledge

Fraunhofer Institute for Building Physics IBP

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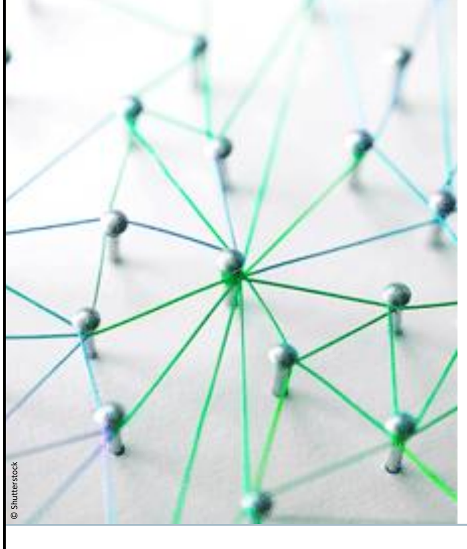
Agenda



01 **Introduction**: Indoor environments, types of pollutants and purification technologies

02 Testing methods: **Realistic conditions** with focus on airborne microorganisms

03 Limitations of established test methods and advantages of **continuous dosing**

04 **Data evaluation**: „Incremental Evaluation Model“ and Example

05 **Transfer of results**: VEPZO model

06 **Outlook**

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1 Introduction

Indoor environments, disturbing components and purification technologies

Indoor environments

- Public buildings
- Schools, hospitals
- **Cinemas**, theaters
- Offices, **meeting rooms**
- Private living spaces
- Underground stations
- Trains
- **Aircrafts**
- Cruise ships
- …

Disturbing components

- Particles
- **Microorganisms**
  Viruses, …
- Evaporative emissions
- Allergens
- Radon

Purification technologies

- Air exchange
- Filtering technologies
- **Inactivating technologies**
  Plasma, **UV-C radiation**
- Reactive gases
  Ozone, …

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2 Testing conditions

Realistic testing conditions – test facilities, air mixing and pollutant source

	Established testing methods	IBP testing methods
Test facilities	▪ Test chambers (e.g. DIN ISO 16000-36: 8 - 30 m³) ▪ Air ducts	▪ **Full-size test rooms** (e.g. test facility 129 m³, cinemas) ▪ Air duct, **Aircraft cabin**
Mixing conditions	▪ Ideal mixing	▪ Ideal mixing ▪ **Device-dependent mixing** ▪ **Thermal air circulation**
Source	▪ Without dosing during test measurement	▪ **Continuous dosing** during test measurement
Evaluation	▪ Exponential decay (loss coefficients k_{AC} and k_{Nat}) ▪ Reduction within 30 min	▪ Process of establishing a **dynamic equilibrium** (k_{AC}, k_{Nat}, source term) ▪ "Incremental Evaluation Model"

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2 Testing conditions

Realistic testing conditions – focus on airborne microorganisms

Realistic interior –
Chairs and tables, cooled "window" surfaces, heated dummies, …

Realistic source –
Breathing head emits a Phi6 aerosol during the test (analogous to breathing)

Airborne phage collection –
Airborne phages are collected on gelatine filters (air volume: approx. 1 m^3)

Phage culture –
Suspension with Phi6 bacteriophage as surrogate for pathogenic viruses

Realistic mixing condition –
Device-dependent mixing or thermal air circulation

Plaque assay test –
Quantification of biological active phages per m^3 (several dilution levels posible)

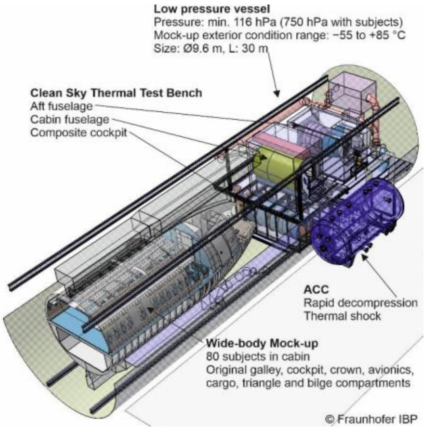
2 Testing conditions

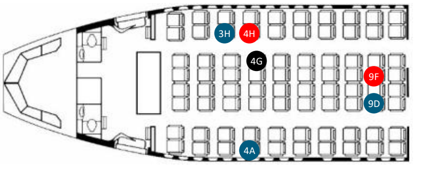
Realistic testing conditions – types of test facilities

Test rooms	Air duct	Aircraft cabin

2 Testing conditions

Realistic testing conditions – aircraft cabin in a low-pressure vessel





- Online particle sampling (Fidas Frog)
- 30min air samples on gel filter (Holbach)
- Breathing head with virus emission (particle generation with Palas device)

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2 Testing conditions

Realistic testing conditions – Real room example: Cinemas

3 Advantages and Challenges of continuous dosing

Limitations of established test methods, advantages of continuous dosing and solutions

Limitations without dosing during measurement

- **Short-circuit** air currents **remain undetected**
- **Less suitable or unsuitable** for **highly effective** systems ($k_{AC} > 20\ h^{-1}$)
- Data analysis is simple

Advantages of continuous dosing during measurement

- **Short-circuit** air currents **can be detected**
- **especially suitable** for **highly effective** systems ($k_{AC} > 20\ h^{-1}$)
- Data analysis is more complex

Challenges (due to continuous dosing and realistic conditions) and solutions

- Data analysis is more complex and requires an evaluation model => **Incremental Evaluation Model** DOI: 10.3390/atmos13101655 and 10.3390/atmos13101575
- The position of the cleaning system and air outlets, the source, the air sample location and the interiors significantly influence the result => **VEPZO Model** DOI: 10.3390/atmos13030389

3 Advantages and Challenges of continuous dosing

Limitations of established test methods, advantages of continuous dosing

Effect of air purification system in the case of a present source at steady state conditions

$$\text{Reduction (R) due to purifying system} = \frac{\text{Concentration } \textbf{with purifying system} \text{ (AC)}}{\text{Concentration } \textbf{without} \text{ purifying system (Nat)}} = \frac{k_{Nat}}{k_{AC} + k_{Nat}}$$

Examples

$$\frac{c(t)}{c_0} = e^{-k_{AC} t}$$

$$R = \frac{k_{Nat}}{k_{AC} + k_{Nat}}$$

			improvement	
k_{AC}	$4.61\ h^{-1}$	$23\ h^{-1}$	Factor 5	
$c_{0.5\ h}/c_0$	10.0 %	0.001 %	4 Orders of magnitude	Source has left the room
k_{Nat}	$0.5\ h^{-1}$	$0.5\ h^{-1}$		
R	9.8 %	2.1 %	Only a factor of 4.6	Source stays in the room
1/R	10.2	47		

4 Evaluation methods

„Incremental Evaluation Model“ – basics and parameters

Formula (concentration profile)

$$c(t) = \frac{s}{[k_{Nat} + k_{AC}]} + \left(c_0 - \frac{s}{[k_{Nat} + k_{AC}]}\right) \cdot e^{(-[k_{Nat} + k_{AC}] \cdot [t - t_0])}$$

Parameter description	Parameter	Unit	type
Concentration, e.g. biologically active Phi6 phages per m³	**c**	$\frac{PFU}{m^3}$	measured
Switching times: source on/off, cleaning system on/off, sampling	**t_0 / t_1 / …**	h	known
Source term, e.g. Phi6 release	**s**	$\frac{PFU}{h \cdot m^3}$	not relevant, if constant
Loss constant without cleaning system	$\mathbf{k_{Nat}}$	h^{-1}	**unknown**
Loss constant of cleaning system	$\mathbf{k_{AC}}$	h^{-1}	**searched**

4 Evaluation methods

„Incremental Evaluation Model“ – basics and parameters

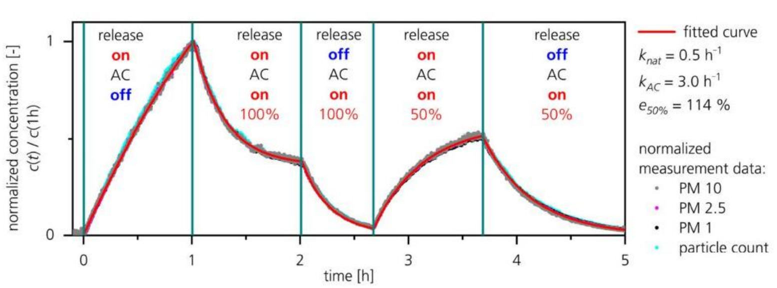


Figure 3. Determination of the coefficient k_{AC} of an air cleaner (AC) in a well-mixed room. The natural loss coefficient is determined between 0 and 1 h. (Fitting process see Section 3.1.2.).

Article

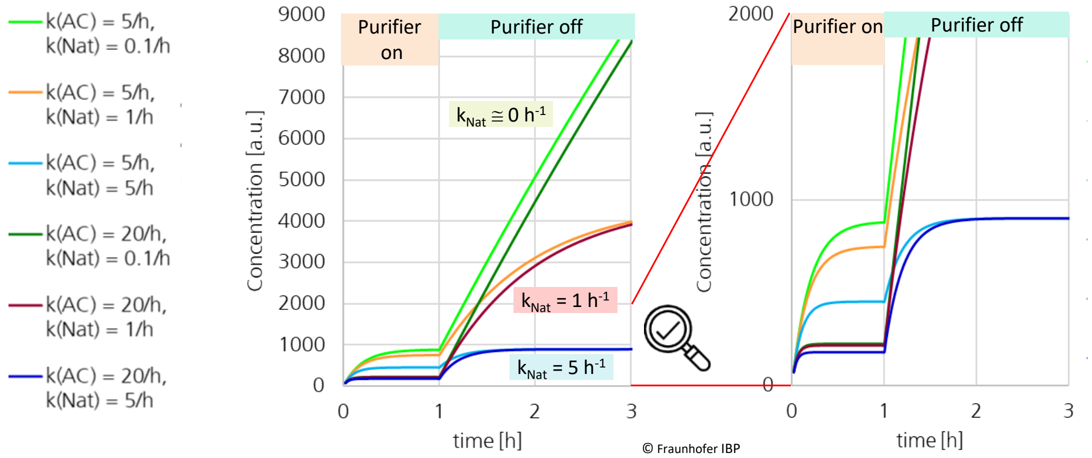
Incremental Evaluation Model for the Analysis of Indoor Air Measurements

Andreas Schmohl, Michael Buschhaus, Victor Norrefeldt, Sabine Johann, Andrea Burdack-Freitag, Christian R. Scherer, Pablo A. Vega Garcia and Christoph Schwitalla

DOI: 10.3390/atmos13101655

4 Evaluation methods

„Incremental Evaluation Model“ – basics and parameters



4 Evaluation methods

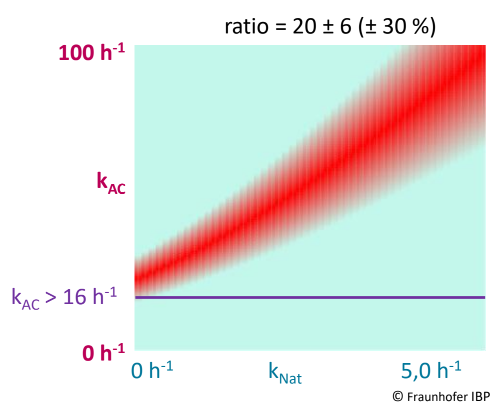
„Incremental Evaluation Model“ – data evaluation with air samples for plaque assays

Ratio of air sample concentrations

$$\frac{c^{\text{air sample}}_{\text{without purifying system}}}{c^{\text{air sample}}_{\text{with purifying system}}} = \frac{f_2(k_{Nat}, k_{AC})}{f_1(k_{Nat}, k_{AC})}$$

only 2 fitting parameters

Parameter description	Parameter	Unit	type
Switching times: e.g. cleaning system off, sampling (start and end)	t_0 / t_1 / …	h	known
Loss constant without cleaning system	k_{Nat}	h^{-1}	**unknown**
Loss constant of cleaning system	k_{AC}	h^{-1}	**searched**



First sampling from 39 min until 59 min, purifier off at 60 min, second sampling from 99 min until 119 min.

4 Evaluation methods

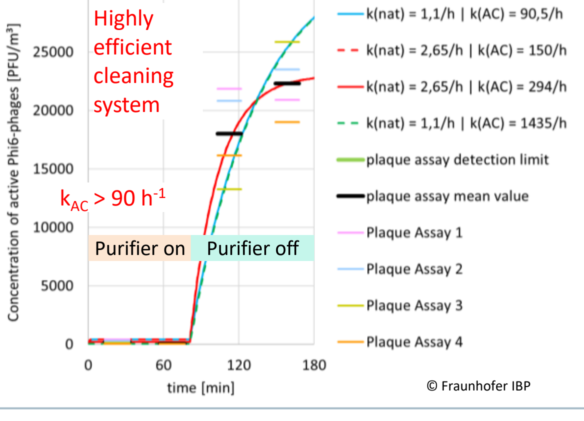
Example: Upper-room LED UV-C cleaning system

Upper room LED array

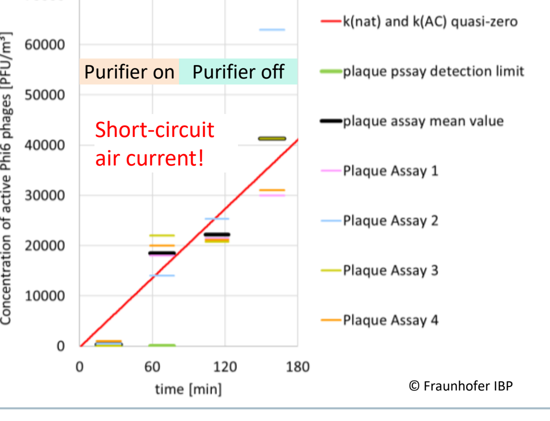
4 Evaluation methods

Example: Upper-room LED UV-C cleaning system

5 m away from the Phi6 source (breathing head) directly in breathing direction



1 m away from the Phi6 source (breathing head) 90° angle to the breathing direction



5 Transfer of results
Transfer of results to other interior rooms

Challenges due to realistic test conditions and solutions

The position of the cleaning system and air outlets, the source, the air sample location and the interiors significantly influence the result

↓

VEPZO Model

DOI: 10.3390/atmos13030389

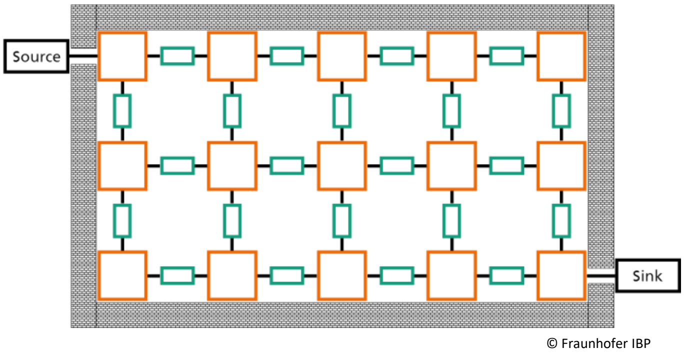
5 Transfer of results: VEPZO model
VEPZO model (VElocity Propagating ZOnal Model) – basics

Subdivision of a space into zones (volumes)

Volume model:
- Mass Conservation
- Conservation of thermal energy
- Conservation of species

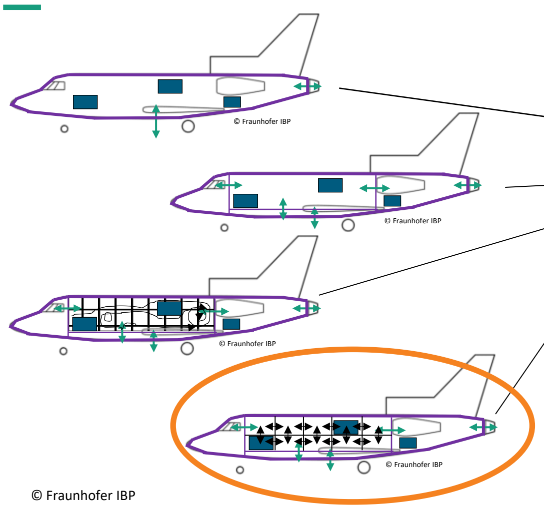
Flow Model
- Simulates flow between adjacent volumes
- Calculates mass flow rate from pressure difference
- Transport of energy and species

Advantages
- Local Resolution
- High simulation speed allowing transient simulations and parameter studies



5 Transfer of results: VEPZO model

VEPZO model – Indoor Environment Simulation Suite (IESS) – Best compromise



Modelling Approach	Local Resolution	Speed, Transient
Single-Zone	-	++
Multizone	0	++
CFD	++	--
Zonal	+	+

Optimum between resolution and speed

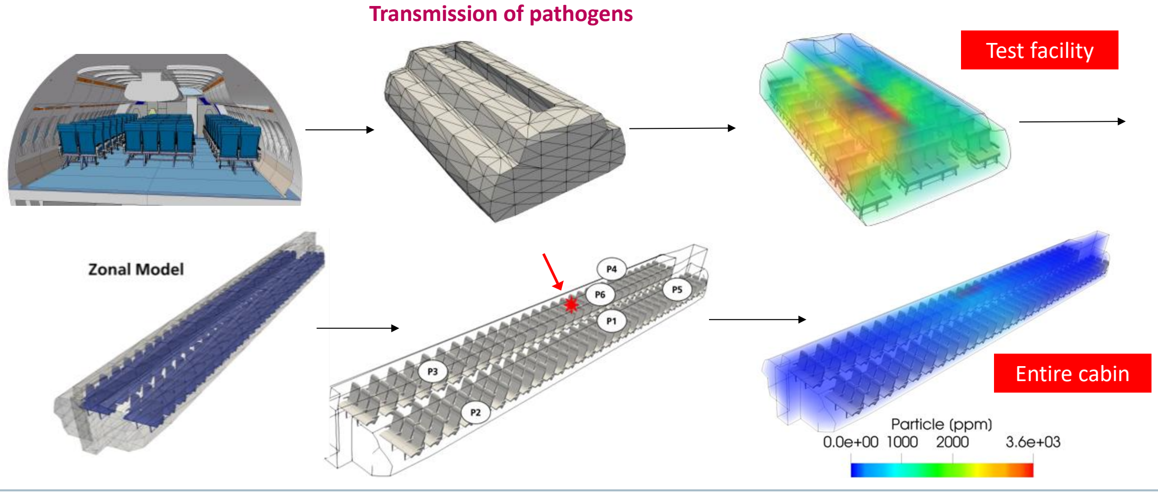
→ **Best compromise**

→ **Fraunhofer IESS**

(Indoor Environment Simulation Suite)

5 Transfer of results: VEPZO model

VEPZO model – Indoor Environment Simulation Suite (IESS) – Aircraft cabin (test facility => real size)



5 Transfer of results: VEPZO model

VEPZO model – Indoor Environment Simulation Suite (IESS) – ICE 4 cabin

Transmission of pathogens

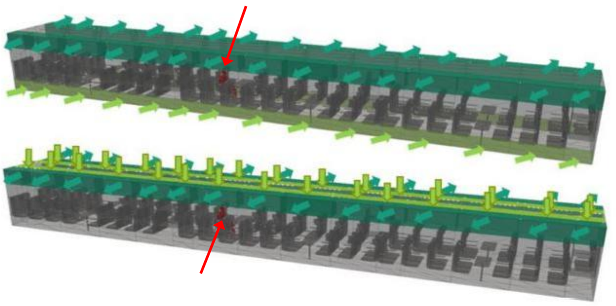


Figure 5. Zonal model of the ICE 4 with sources and sinks for heating (**top**) and cooling (**bottom**) mode: light green arrows, supply air; dark green arrows, exhaust air; red-marked person, emitter.

Article

Modeling the Airborne Transmission of SARS-CoV-2 in Public Transport

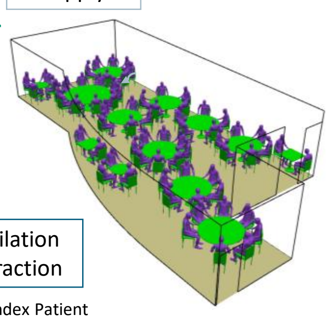
Christina Matheis, Victor Norrefeldt, Harald Will, Tobias Herrmann, Ben Noethlichs, Michael Eckhardt, André Stiebritz, Mattias Jansson, and Martin Schön

DOI: 10.3390/atmos13030389

5 Transfer of results: VEPZO model

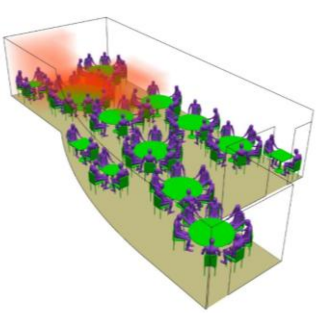
VEPZO model – Indoor Environment Simulation Suite (IESS) – Restaurant

Transmission of pathogens



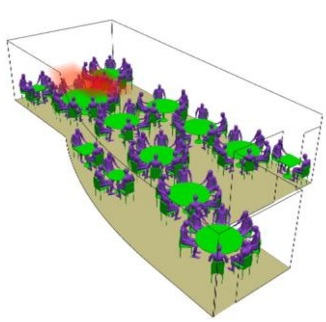
- One Index Patient
- Airflow rate :1 l/s per person
- Air supply at ceiling (centre)
- Air extraction at floor level (left and right)

Poor Ventilation



spreading area (highlighted in Red)

Improved Ventilation



spreading area (highlighted in Red)

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6 Outlook

- Testing of diverse – in particular inactivating – purification technologies and highly effective purification systems ($k_{AC} > 20\ h^{-1}$)
- Combinations of purification systems and influence of humidity and temperature => synergistic effects?!
- Further development of VEPZO model for airborne microorganisms
- Validation of VEPZO results for airborne microorganisms
- Development of a planning tool for air purification systems => Hygiene concept
- Consideration and reduction of energy consumption and noise
- Cost-benefit analysis

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Thank you for your attention

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