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京都大学	博士（　工学　）	氏名	Wenlu Wang
論文題目	Laboratory Simulation and Evaluation of Aerosol Particles Penetration, Deposition and Removal Processes in Sheltering Houses Equipped with Ventilation Systems (換気システムを備えた待避家屋におけるエアロゾル粒子の侵入、沈積および除去プロセスの実験室シミュレーションと評価)		

（論文内容の要旨）

This thesis presents in-depth information on the behavior and mechanism of aerosol particles in the process of penetration, deposition and removal in sheltering houses equipped with ventilation systems by laboratory simulation and evaluation. The thesis was divided into 7 chapters with each of the chapter cover various part as followed:

Chapter 1. Introduction

This chapter introduces the background of the accident at the Fukushima Daiichi Nuclear Power Plant and its impacts on the surrounding air. In addition, the objectives and the structure of this research are also introduced.

Chapter 2. A Review of Research on Aerosol Particles Penetration from Outdoor to Indoor

In this chapter, the referred properties of aerosol particles of this thesis are introduced. Moreover, literatures concerning the research progress of aerosol penetration are reviewed.

Chapter 3. Simulation and Evaluation of Sheltering Efficiency of Houses Equipped with Ventilation Systems

Experiments in this chapter investigate various elements that may affect the penetration factor, categorize particles (especially for UFPs) by the penetration characteristics for universal household sliding windows, reveal the most effective sheltering configuration for houses in air pollution emergencies, and compare the differences between the completely ideal state (uncharged/neutralized) and the actual situation through the particle charging state. The results illustrate that a high air exchange rate corresponds to a high penetration factor, and the concentration difference between outdoor and indoor affects ventilation efficiency. For universal household sliding windows, frames made of plastic coupled with an air exchange rate less than or equal to 1.20 h^{-1} can prevent particle penetration more effectively in air pollution emergencies. As the external particles gradually disperse and the concentration decreases, a ventilation system with a large air exchange rate may effectively purify the indoor air. However, UFPs of less than 69 nm are able to undergo penetrate in a large amount, especially when the air exchange rate is lower than 1.20 h^{-1}. Therefore, effective housing sheltering is still a challenge if the external source is primarily UFPs. The laboratory results of this work provide a reference for emergency evacuations and indoor air quality improvements when environmental air pollution accidents and extreme weather occur.

Chapter 4. Determination of the Optimal Penetration Factor for Evaluating the Invasion Process of Aerosols from a Confined Source Space to an Uncontaminated Area

Due to the outbreak and spread of COVID-19, SARS-CoV-2 has been proven to survive in aerosols for hours. To evaluate the invasion process of virus-containing aerosols from a confined source space to an uncontaminated area, based on the work in chapter 3 and a widely used concentration model, four numerical calculations of the penetration factor are proposed in this chapter. A theoretical time-correction P_{est} was applied to a size-dependent P_{avg} by proposing a correction coefficient r, and the error analysis of the real-time P(t) and the derived P_d were also performed. The results indicated that P_{avg} supplied the most stable values for laboratory penetration simulations. However, the time-correction is of little significance under current experimental conditions. P(t) and P_d are suitable for rough evaluation under certain conditions due to the inevitability of particles detaching and re-entering after capture. The proposed optimal P value and the error analysis could help provide insight into the penetration mechanism, and can also provide a rapid and accurate assessment method for preventing and controlling the spread of the epidemic.

Chapter 5. A Review of Indoor Particles: Behavior and Ventilation Technology

In this chapter, the behaviors of indoor particles, including deposition and coagulation, and the research progress of that under ventilation is reviewed.

Chapter 6. Assessment of Air Purification Effect in Sheltering Houses Equipped with Ventilation Systems after Air Pollution Incidents

A key issue in the later stage of an environmental emergency is indoor air purification. This chapter investigates a reasonable ventilation strategy for indoor air purification in the later stage of an air pollution accident. Using a closed test chamber to simulate a sheltering house with a ventilation system, the deposition rates of aerosol particles were measured under both ideal and non-ideal conditions. Additionally, the actual turbulence state can be inferred by querying the optimal K_e in the β-K_e diagram proposed by this work. The main removal mechanism for particles within the range of 53.3–371.8 nm at an air exchange rate less than 1.19 h^{-1} is deposition. A ventilation system based on a high-power exhaust pump causes a large turbulence, which results in the resuspension of particles outside the cumulative mode range with a ‘sudden drop’ in the deposition rate. In the later stage of an air pollution accident or in the case where outdoor particles do not contribute indoors, turning off other stirrers and fans and increasing the AER value of the ventilation system to more than 1.19 h^{-1} can achieve the desired air purification effect. This study provides a reference to improve the indoor air quality in the event of an air pollution accident. It also provides effective information for general household air purification. Additionally, it can support the construction of shelters in areas and countries prone to air pollution accidents or floating dust/hazy weather.

Chapter 7. Conclusions and Perspectives

The main findings and limitations of this study are summarized and emphasized.

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（論文審査の結果の要旨）

本論文は、福島第一原発事故のような大気汚染事故が発生し、放射能雲が近づいてきて屋内退避するような場合に、放射性エアロゾルの屋外から屋内への侵入率、屋内での沈積率、屋外への排除率、など屋内退避のリスク評価に影響する因子を実験により検討した成果をまとめたものであり、得られた主な成果は以下のとおりである。

1. 有害エアロゾル粒子が発生する大気汚染事故で一般住居を待避場所とした場合、空気交換率の大きな時に粒子の侵入率は大きくなるが、一般的な住居のスライド窓の場合、プラスチック枠で空気交換率が 1.2 h^{-1} 以下の場合は、通常の有害エアロゾル粒子の侵入は十分有効に防げることがわかった。しかし、69 nm 以下の超微細粒子(UFP)は空気交換率が 1.2 h^{-1} より小さくても大量に侵入することができることから、室外の主たる有害粒子が UFP の場合には、待避場所として有効な家屋を実現することは困難であることを明らかにした。

2. 同程度の大きさの室外模擬空間と室内模擬空間を接続した本研究の閉鎖型実験チャンバーにおいて、エアロゾル粒子量として初期存在量のみがある場合、測定値から侵入率 P を算出するいくつかの方法を比較した。空気中濃度が変化しない場合の算出式に、粒径毎の時間平均濃度を代入して求めた侵入率 P_{avg}、さらにそれに理論的時間補正係数 r を適用した P_{est} を比較すると、時間補正係数 r の考慮が必要となるのは、室外空気濃度が室内濃度よりもはるかに高い場合や、空気交換率が 3.7 h^{-1} といった大きな値の場合と考えられた。各時刻ごとの濃度を上記の算出式に代入して侵入率を計算する方法も本研究の実験条件では 1.2 h^{-1} といった空気交換率が小さい場合には適用可能であるが、空気交換率や濃度変化の影響を受けにくい P_{avg} が実用的には最良と考えられた。

3. 大気汚染事故後の室内空気浄化のための換気方法について、閉鎖型実験チェンバーを用いた実験を行って検討した。エアロゾル粒子の沈降率を様々な荷電状態の場合について測定し、また、室内空気の乱流強度を示すパラメーター値の推定も行った結果、粒径 53 – 370 nm で空気交換率 1.2 h^{-1} 未満の場合の主たる除去メカニズムは室外への排出ではなく室内での沈着・沈降などであること、換気システムの空気交換率を 1.2 h^{-1} 以上にすることで、乱流発生の効果が大きくなり、大きな空気清浄効果が得られることなどを示した。

以上の結果は、大気汚染事故において屋内退避する場合のリスク評価を行うための貴重なデータを提供するものであり、また、大気汚染事故に対する避難所の設計にも大きく貢献するものであって、学術上、実際上寄与するところが少なくない。よって、本論文は博士（工学）の学位論文として価値あるものと認める。また、令和２年８月２５日、論文内容とそれに関連した事項について試問を行って、申請者が博士後期課程学位取得基準を満たしていることを確認し、合格と認めた。なお、本論文は、京都大学学位規程第 14 条第 2 項に該当するものと判断し、公表に際しては、当該論文の全文に代えてその内容を要約したものとすることを認める。

要旨公開可能日：　　　　　　年　　　　月　　　　日以降