Received: 0 0000 | Revised: 0 0000 | Accepted: 0 0000
DOI: 10.1002/jar3.1

TRANSLATED ARTICLE

WILEY Journal Logo

Net escape probability of contaminant from a local domain to exhaust outlet

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Funding information
JSPS KAKENHI, Grant/Award Number: JP 16H04466

Abstract

Ventilation is essential to control contaminant concentration in a room, and hence, the evaluation of ventilation effectiveness is crucial to achieve a clean, healthy, and energy-saving indoor environment. In general, the contaminant transport efficiency is defined by total flux, ie, convective and diffusive fluxes of the contaminant in a local domain. The fluxes are divided into two components: (i) the contaminant is directly exhausted through exhaust outlet in the room and does not return to target local domain and (ii) the contaminant is returned to the target local domain by a recirculating flow in the room. In this study, we propose a calculation procedure of net escape probability of a contaminant that is constantly generated in the target local domain.

KEYWORDS
ventilation effectiveness, net escape velocity, net escape probability, returning probability

1 | INTRODUCTION

Ventilation involves exchanging contaminated indoor air with clean (generally outdoor) air. From a specification standpoint, the amount of air introduced is stipulated, for example, room ventilation frequency of 0.5 times/h or more. However, from a performance regulation standpoint, a guaranteed amount of clean air is needed to control the concentration of contaminant below a threshold. Regarding the general environment, the purpose of supplying clean air through the appropriate ventilation is to maintain a hygienic and healthy environment for the residents, which makes the control of air environment crucial in local areas such as residential and breathing zones. Although introducing outdoor air immediately results in increasing the air-conditioning load from an energy-saving standpoint, control of air environment in local areas can eliminate energy waste resulting from supplying clean air to areas far from the occupant zone, such as the ceiling. Based on this concept, several studies have contributed to the knowledge about ventilation efficiency, resulting in many practical applications.[1–3]

This article is the English language translation of an article that has been published in Japanese in [journal title, with full reference].

The purpose of this study was to discuss in depth about indoor ventilation effectiveness in the limit value of a local domain.

As mentioned above, one aspect of ventilation effectiveness from a performance standpoint is the "control of average contaminant concentration in a local domain." This average contaminant concentration in a local domain is determined by the amount of contaminant generated, the location, and the amount of clean air. However, as the indoor air field is a strongly non-linear field defined by the Navier-Stokes equation, it is difficult to estimate the "average contaminant concentration in a local domain" without assuming a simplified ideal flow field with perfect mixing and instantaneous uniform diffusion. The "average contaminant concentration in a local domain," which is defined based on the assumption of a non-uniform mixed flow field in a room, takes a different value than the advective air velocity (the product of average air velocity at the boundary and cross-sectional area of the advective flow) flowing into the local domain, and this net ventilation air volume that determines the average contaminant concentration at this local domain is called local purging flow rate (*L-PFR*).[4–7]

The average contaminant concentration at the local domain and the *L-PFR* depend on the size of the target local domain. As the local

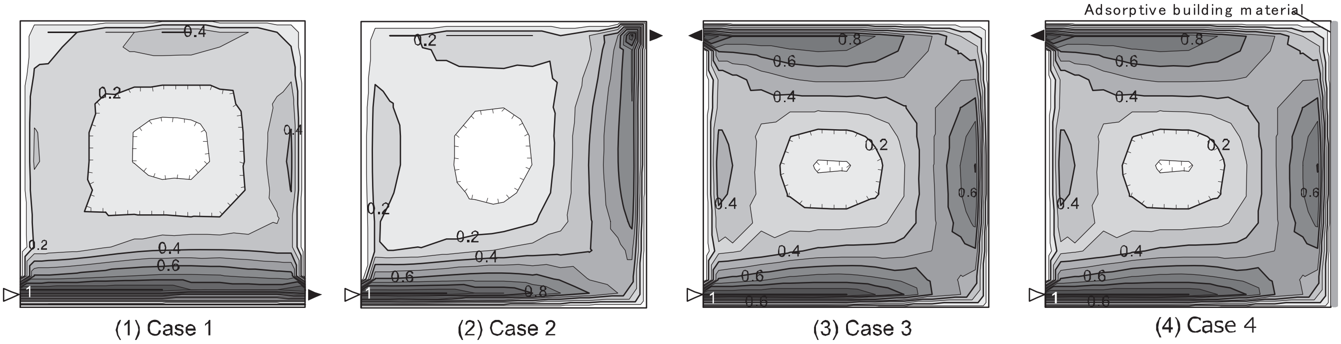

FIGURE 3 Distributions of velocity magnitude (U_{in}=1.0)

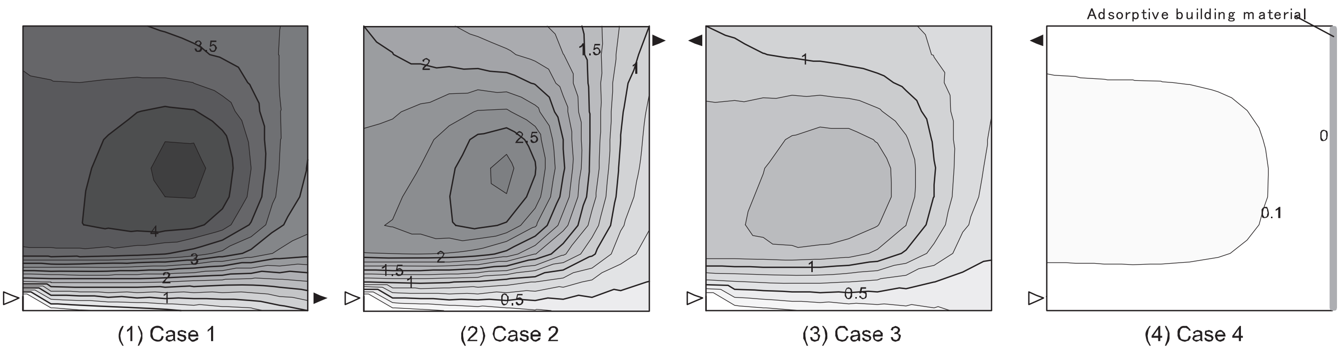

FIGURE 4 Distributions of contaminant concentration under uniform contaminant generation in the space [-]

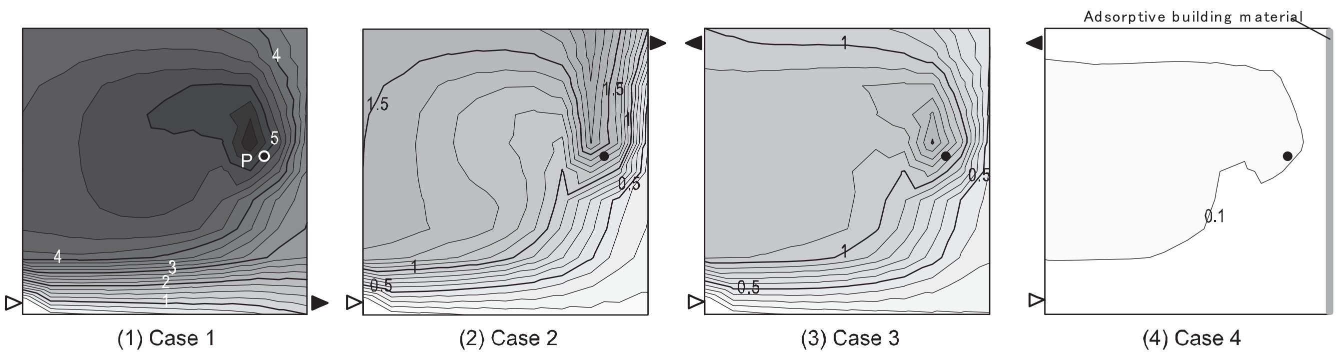

FIGURE 5 Distributions of contaminant concentration under contaminant generation at point P in the space [-]

cases, while no large differences were observed between the advective air velocity vector and *NEV** vector, a detailed comparison revealed a certain difference in size and direction between the vectors. Overall, *NEV** has been evaluated to be generally larger compared to the advective air velocity, and it largely confirms the presence of a certain extent of the diffusion effect due to contaminant distribution gradient (turbulent flow). The results suggest that the direction of the advective flow and the direction of the concentration gradient (direction of diffusion) are the same; if the directions of advection and diffusion were different, then *NEV** would be evaluated to be lower than the advective air velocity scale. When comparing Case 3 with Case 4 (with an adsorptive wall facing the supply inlet), no significant differences were observed in the *NEV** distribution; however, for *NEV** at the first CV from the wall facing the supply inlet, the NEV_x^* component is evaluated to be about 2-3% larger in Case 4 than in Case 3, because of the effect of the diffusion component on the adsorptive surface. Under the conditions of this analysis, the diffusion flux from the target CV is almost always outward due to isotropic diffusion, because in *NEV** calculations, the contaminant generation occurs only at the target CV. In spite of the presence of a constant adsorptive flux toward the adsorptive surface in the CVs adjacent to the adsorptive wall, there also exists a constant diffusion flux in the opposite direction (toward the space), and they cancel each other out in NEV_x^* calculations, resulting in a dominant NEV_x^* component parallel to the adsorptive surface.

5.4 | RP and NEP distribution

Figure 7 shows the results of the analysis of RP (Equation 4) distributions. The results of the analysis of NEP (Equation 5) distributions are shown in Figure 8. Similar to NEV* shown in Figure 6, the RP and NEP for each CV shown here were calculated based on a steady flow field information and the information on the average concentration field obtained by a sequential contaminant generation in each CV (10×10 times of concentration field calculations were performed corresponding to the number of meshes used in calculating the NEP distribution shown in Figure 8).

In all the cases, at the CVs adjacent to the supply inlet and the exhaust outlet, the *RP* was close to 0, with *NEP* approaching a value of 1. The results indicate that although the contaminant generated in the CVs adjacent to the supply inlet and the exhaust outlet may traverse different flow paths within the room after escaping from the CV, more than half of it does not return, likely due to the direct purging through the exhaust outlet. RP is relatively lower and NEP is relatively higher also at the stagnant region near the room center and at the corners without supply inlet or exhaust outlet. In the stagnant region, the transport of the contaminant generated in the CV is dominated by diffusion, and the results quantitatively demonstrate that the probability of the contaminant returning due to advective flow is low. As shown in Figure 8, the NEP distribution represents the probability of transportation of the contaminant generated at each point in the diagram toward the exhaust outlet (without ever returning to the respective points). It also quantitatively indicates the contaminant exhaust path (or the ventilation dilution path). However, it must be noted that it does not include the concept of the scale of time required for the exhaust.

5.5 | *NEV* distribution

We have proposed two definitions of the transport velocity scale that determines the contaminant concentration at local points, given by *NEV* (Equation 6) and *NEV** (Equation 7). As shown in Equation 10, these are integrated by using *NEP*, which is the probability of the net exhaust of the contaminant. Figure 9 shows the $|NEV^*|$ distribution given by Equation 7, and Figure 10 shows the *NEV** distribution, which is the same as $|NEV|$ distribution given by Equation 6. Comparing these with the average scalar air velocity (advective air velocity), distribution shown in Figure 3 reveals that as the contaminant leaves the local point (CV), the contaminant transport velocity $|NEV^*|$ becomes greater than the advective air velocity, and the difference between the advective air velocity and $|NEV^*|$ shows the component that is transported out of the local point due to diffusion of the contaminant. It is also observed that $|NEV|$, which is the exhaust speed scale component for the contaminant exhaust path leading directly to the exhaust outlet without returning to the point of generation after the contaminant escapes the local point (CV), becomes smaller than the advective air velocity.

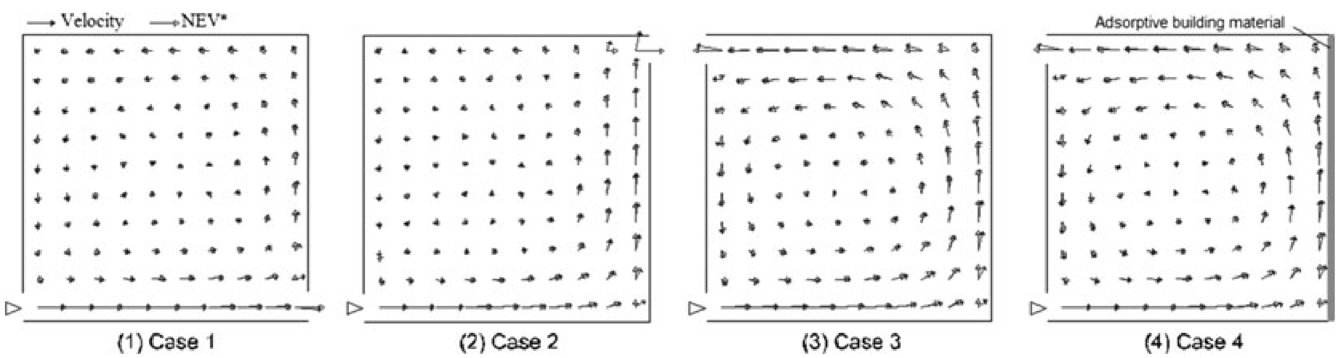

FIGURE 6 Vector distributions of airflow (advection) and NEV* (U_{in}=1.0]

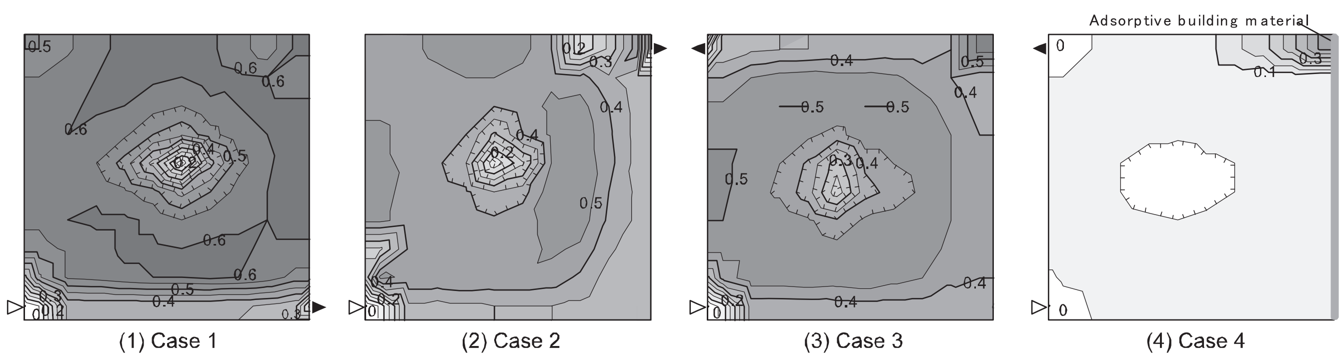

FIGURE 7 Distributions of returning probability [-]

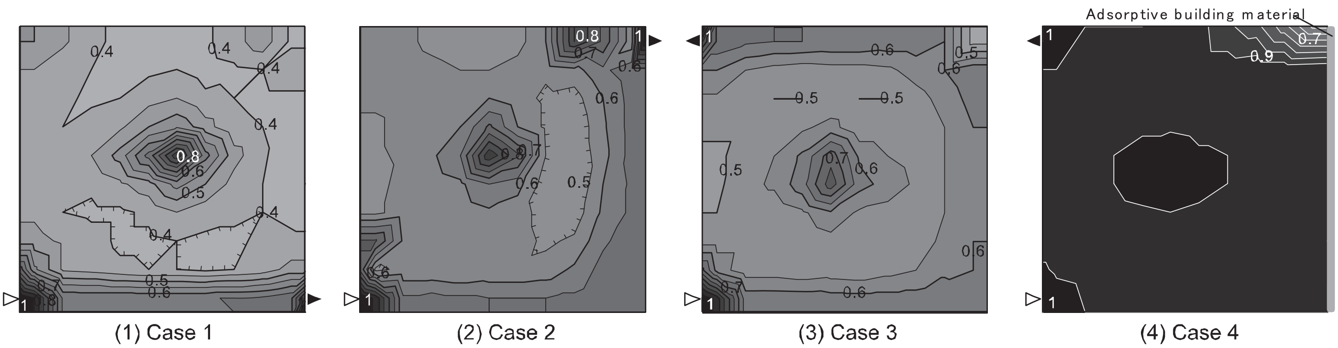

FIGURE 8 Distributions of net escape probability [-]

6 | DISCUSSION AND FUTURE CHALLENGES

In this paper, to facilitate the discussions on one limit (extreme value) of ventilation efficiency at an indoor local domain, assuming the CV in CFD analysis to be a point mass, a method, to calculate the probability of contaminant returning to the local point where it was generated (RP) and the probability that the contaminant is exhausted directly through exhaust outlet and does not re-circulate to the target local domain (*NEP*) using the results of average diffusion field analysis based on RANS model, has been proposed, and the results of the numerical analysis using a simple two-dimensional room model have been described.

The average contaminant concentration or the concentration non-dimensionalized by perfect mixing concentration at a local point provides essential information while considering the ventilation efficiency at that point. The average concentration of this local point will be controlled by the design goal or the value below the threshold set in various environmental standards. However, for effective control of this concentration, it is necessary to comprehend the mechanism of average concentration formation. For example, when *NEV**, representing the transport velocity of the contaminant, and *NEP* are both large, the contaminant (both returning and generated) quickly leaves the point of interest due to advection and turbulent diffusion, and exhibits a high probability of being directly purged through the exhaust outlet without any recirculation, resulting in a large *NEV* as defined by Equation 10 at this point. In ventilation design, one can grasp the degree of concentration dilution due to turbulent diffusion by comparing this *NEV** with the average air velocity (advection speed) at the point of interest, while the *NEP* value helps grasp the relative position of the point in question on the virtual ventilation path from the supply inlet to the exhaust outlet. This is the intention behind the aforementioned "comprehending the mechanism of average concentration generation at a local point." However, the practical control parameters in ventilation design are the supply inlet layout and air volume, and considering that the flow field is highly non-linear, the results of adjusting these parameters suggest that it is impossible to quantitatively grasp their effect on *NEV** or *NEP* without performing analysis under new boundary conditions. The problem of determining an appropriate layout and air volume, based on *NEV** and *NEP* values, actually belongs to the category of inverse problem analysis, and in this area, many studies such as three-dimensional or four-dimensional variational assimilation are being pursued. The authors believe that further studies including inverse problem analysis are required to advance the goal of analysis on *NEV** and *NEP* from comprehending the mechanism of average concentration generation at a local point in order to use it as a practical ventilation design tool.

The *NEP* and *NEV* are quantitative indicators for discussions regarding "efficiency concerning contaminant transport from a target local point to the exhaust outlet, in a series of ventilation airflow path from the supply inlet to the exhaust outlet." NEP indicates the probability that the contaminant generated at the target local domain is exhausted directly through exhaust outlet, and assuming that the air or contaminant mass flowing through this target domain enters the next domain downstream of the target domain and follows either a path without returning to the target domain directly to the exhaust outlet, or a path that involves at least once returning to the target domain, the percentage of contaminant transport volume in the former is given by *NEP*, while in the latter, it is given by RP.[†] *NEV** represents the contaminant transport velocity concerning all the possible transport paths downstream of the target domain, whereas *NEV* represents the contaminant transport velocity (this is different from advective air velocity) concerning the paths downstream of the target domain leading directly to the exhaust outlet.

Assuming that the concentration is constant in the target domain if *NEV** at this point is large, but the *NEP* is small, then it indicates that although the transport velocity of the contaminant generated is high, it may repeatedly return to the target domain. If *NEV** is small and *NEP* is large, then it indicates that although the transport velocity of the contaminant generated is low, it means that the contaminant moves directly toward the exhaust outlet without returning to the target domain. These are concisely represented by *NEV*, integrating *NEV**and *NEP*. The authors believe that ventilation efficiency analysis using *NEV*, *NEV**, and *NEP* will be effective in evaluation of cases where the contaminant concentration cannot be determined solely from advective air velocity and ventilation air volume, or where the concentration is greatly affected by an adsorptive flux due to the presence of adsorptive materials, or where a concentration attenuation occurs due to chemical reactions in the air.

The authors also believe that the discussions based on local "point" presented in this paper will be extensible to local domain with a finite volume, and applicable in regulating ventilation efficiency in breathing and residential zones. Therefore, the authors hope that the discussions on average concentration formation mechanism at a "point" treated as a limit of the local domain will be helpful to other researchers.

ACKNOWLEDGMENTS

This work was supported by JSPS KAKENHI grant number JP 16H04466. The authors express special thanks to the funding source.

ENDNOTES

¶ *NEV* and *NEV**, as defined in Equations 6 and 7, are derived based on mass balance at the CV that is assumed to be a virtual local point. Therefore, in discussions based on a one-dimensional model, the inflow and the outflow areas corresponding to the virtual CV are assumed to be equal. The assumption of inflow area and the outflow area being equal does not strictly hold if this formulation is extended to a three-dimensional CV. Therefore, in a three-dimensional CV, it is necessary to use adjusted inflow flux F'_{inflow}, such that the inflow area equals the outflow area, by adjusting the inflow flux F_{inflow} using the ratio ($A_{inflow}/A_{outflow}$) of inflow area A_{inflow} and outflow area $A_{outflow}$, when deriving Equation 10 from Equations 8 and 9.
Assuming uniformity is preserved within the CV, and given that the CV has the lowest resolution scale in CFD analysis, it is considered rational to formulate *NEV* and *NEP* using the inflow/outflow flux based on the assumption that the inflow area equals the outflow area.

† For example, if at a local point, *NEP*=0.7 and RP=0.3, it implies that 70% of the contaminant flowing along the path through the point will be purged outdoor directly along a path toward the exhaust outlet without returning to the point, while 30% of it will be returning at least once to the point in question traversing various flow paths in the room. The conceptual diagram is shown in Figure A1.

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How to cite this article: Lim E, Ito K. Net escape probability of contaminant from a local domain to exhaust outlet. *Jpn Architect Rev*. 2017;00:1–8. https://doi.org/10.1002/jar3.1

APPENDIX

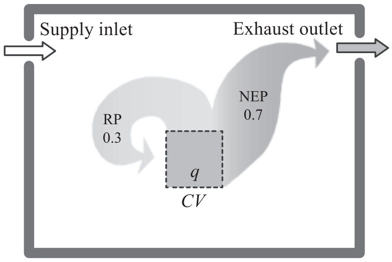

FIGURE A1 Conceptual diagram of *NEP* and *RP* at a local point