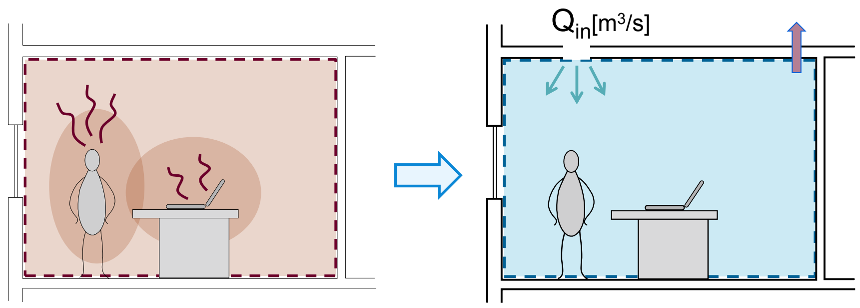
Evaluation of ventilation efficiency in a local domain using *Net Escape Velocity* and *Net Escape Probability*

Eunsu LIM（Toyo University）

Contents

Background



Polluted room

Ventilated room

- Purpose of ventilation design:

  to replace the polluted air with fresh air

Ventilation Design

- Methods of Ventilation Design :
  - Air exchange rate
  - Supplying fresh air
  - Removing contaminant

are related to the distribution of flow and diffusion fields

To evaluate the ventilation efficiency at a local domain is important.

Indices of ventilation efficiency

The several indices of ventilation efficiency for evaluating a local domain have been proposed.

Research Level

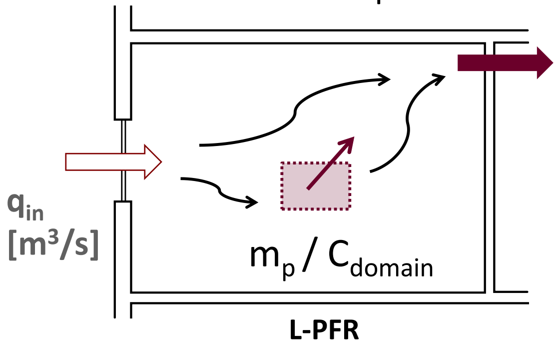
- The age of air (Sandberg, 1981)
- The Scale for Ventilation Efficiency (SVE1~6) (Kato and Murakami, 1986)
- Local Purging Flow Rate (Sandberg and Sjöberg, 1983)

Practical Level

- The air change effectiveness – ASHRAE-s in US
- The normalized concentration in an occupied zone – SHASE-s in Japan

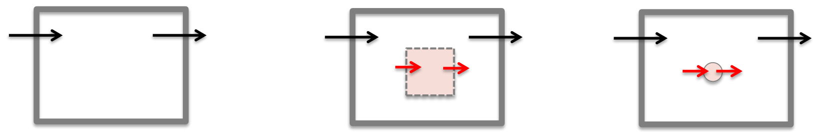
Local-Purging Flow Rate (L-PFR)

- The flow rate to dilute/remove contaminant generated in a target local domain. [m^3/s]
- The flow rate that defines the average concentration of the local domain. L-PFR is not equal to the flow rate q_{in}



The minimum scale of Ventilation Efficiency

Target area

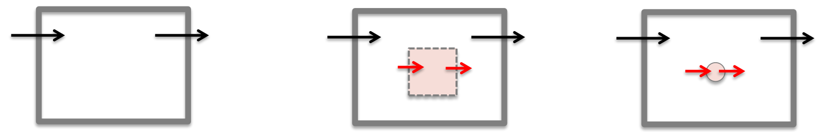


Air flow rate	L-PFR	?
m^3/s	m^3/s	m/s

- The average concentration of the target area is determined by the amount of contaminant generated and the air flow rate
- When L-PFR is defined at a "point", the scale will be air velocity dimension [m/sec] → ??

The minimum scale of Ventilation Efficiency

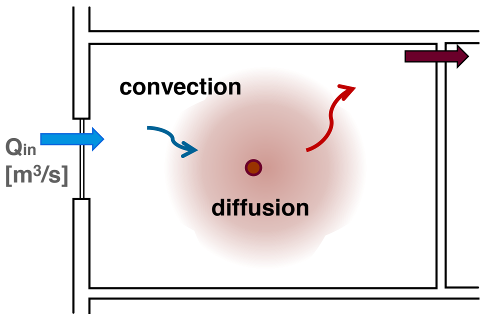
Target area



Air flow rate	L-PFR	NEV
m^3/s	m^3/s	m/s

- The average concentration of the target area is determined by the amount of contaminant generated and the air flow rate
- When L-PFR is defined at a "point", the scale will be air velocity dimension [m/sec] → Net Escape Velocity (1997, Sandberg)

The transport of contaminant



Transport of contaminant

Contaminant transport is governed by convection and diffusion phenomena

Net Escape Velocity

the effective velocity of contaminant transport/dilution at a target point

- **Net Escape Velocity** is defined by the concentration of contaminant, convective flux and diffusive flux at the target point

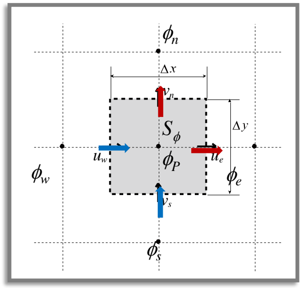
$$NEV_x = \frac{F_{outflow,x} - F_{inflow,x}}{\phi_{CV}}$$

- On premise of numerical calculation:

  the CV → the point

Assumption (CFD)

On the premise of discretization by the finite volume method,



Volume integration in CV

⇒ In CV assumed to be uniform

↓

CV can be thought of as a mass point

↓

The amount of contaminant dilution for CV

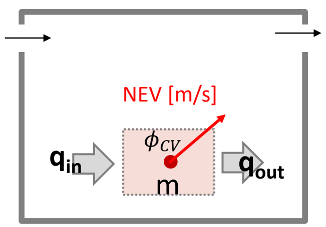
Instead of flow rate scale,

Express on the representative velocity scale

Net Escape Velocity

NEV, [m/s]

The velocity of contaminant at a CV is diluted/removed from the CV, never returning.



$$NEV_x = \frac{1}{\phi_{CV}}\left\{\left(u_x\phi\big|_{out} - D_{eff}\frac{\partial\phi}{\partial x}\bigg|_{out}\right) - \left(u_x\phi\big|_{in} - D_{eff}\frac{\partial\phi}{\partial x}\bigg|_{in}\right)\right\}$$

$$= \frac{F_{outflow,x} - F_{inflow,x}}{\phi_{CV}}$$

ϕ_{CV} : Contaminant concentration in target CV [kg/m³]

D_{eff} : Effective diffusion coefficient [-], $D_{eff} = D + \nu_t \ /\sigma_t$

σ_t : Turbulent Schmidt number [-]

q_{in}, q_{out} : the amount of contaminant flowed in the CV [kg/s]

Definition of Net Escape Velocity

Vector quantity

$$NEV_x = \frac{1}{\phi_{CV}}\left\{\left(u_x\phi\big|_{out} - D_{eff}\frac{\partial\phi}{\partial x}\bigg|_{out}\right) - \left(u_x\phi\big|_{in} - D_{eff}\frac{\partial\phi}{\partial x}\bigg|_{in}\right)\right\} \quad \cdots(1)$$

Convection flux | Diffusion flux

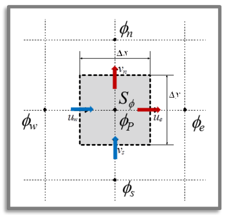
Outflow flux

Inflow flux

→ Source

Magnitude

$$\overline{NEV} = \sqrt{\overline{NEV_x}^2 + \overline{NEV_y}^2 + \overline{NEV_z}^2} \quad \cdots(2)$$

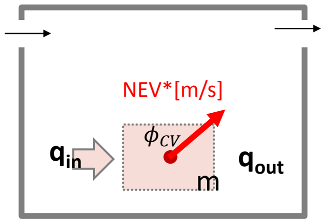


Control volume

Net Escape Velocity Star (NEV*)

NEV* , [m/s]

The velocity of contaminant at a CV is transported from the CV.



$$NEV_x^* = \frac{1}{\phi_{CV}}\left(u_x\phi\Big|_{out} - D_{eff}\frac{\partial\phi}{\partial x}\Big|_{out}\right) = \frac{F_{outflow,x}}{\phi_{CV}}$$

ϕ_{CV} : Contaminant concentration in target CV [kg/m^3]

D_{eff} : Effective diffusion coefficient [-], $D_{eff} = D + \nu_t \;/\sigma_t$

σ_t : Turbulent Schmidt number [-]

q_{in}, q_{out} : the amount of contaminant flowed in the CV [kg/s]

Comparison of Fluid mechanics and Ventilation

- **Properties**

Fluid mechanics	Ventilation
Flow of all fluid particles	Flow of fluid particles never returning
Velocity of any fluid particle	(Flow of fluid particles never returning)/(control surface)

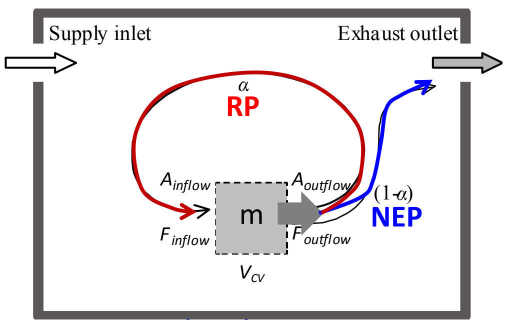
- **Corresponding terminology**

Fluid mechanics	Ventilation
Flow rate	Purging Flow Rate
Velocity	Net Escape Velocity

Transport component of indoor-generated contaminants

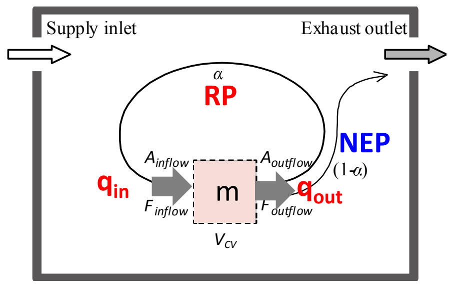
Transport component of contaminants generated at the target mass point (CV) will be divided to 2 components.

- Component to be removed directly through the exhaust outlet
- Component returning to generation point (CV) by circulating flow



Net Escape Probability (NEP) **Returning Probability (RP)**

Ventilation index NEP, RP



Conceptual Diagram of NEP and RP

Returning Probability (RP)

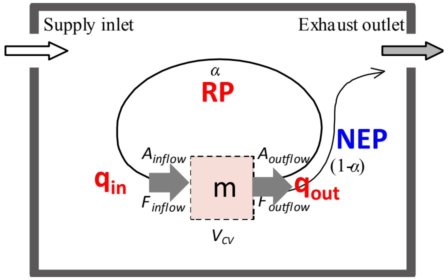
$$\alpha = \frac{q_{in}}{q_{out}} = \frac{q_{in}}{q_{in}+m}$$

Net Escape Probability (NEP)

$$1-\alpha = \frac{q_{in}}{q_{out}} = \frac{m}{q_{in}+m}$$

Ventilation index NEP, RP

Returning Probability (RP)



Conceptual Diagram of NEP and RP

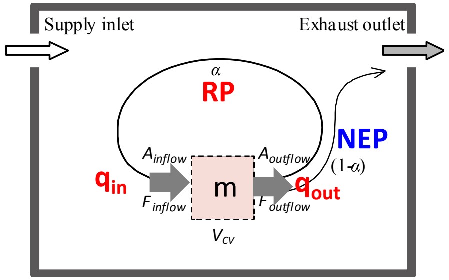
$$\alpha = \frac{q_{in}}{q_{out}} = \frac{q_{in}}{q_{in}+m}$$

$$= \frac{F_{inflow}A_{inflow}}{F_{inflow}A_{inflow} + qV_{CV}}$$

$$= \frac{F_{inflow}A_{inflow}}{F_{outflow}A_{outflow}}$$

Ventilation index NEP, RP

Net Escape Probability (NEP)



Conceptual Diagram of NEP and RP

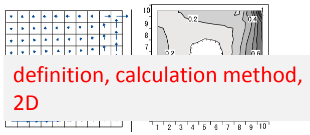
$$1-\alpha = \frac{q_{in}}{q_{out}} = \frac{m}{q_{in}+m}$$

$$NEP = \frac{qV_{CV}}{F_{outflow}A_{outflow}}$$

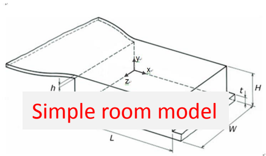
Our works

- Definition of Net Escape Velocity and analysis by RANS model, **NEV and NEP**
- Application of NEV to 3D flow field / contaminant diffusion field
- Application of NEV to air quality control problem for various local ventilators, **NEV and NEP**

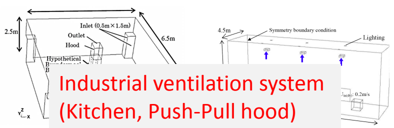
$$NEV_i = \frac{1}{\phi_{cv}}\left(\overline{u_{out}\phi_{out}} - D_{eff}\frac{\partial \phi}{\partial y}\Big|_{out}\right)$$



definition, calculation method, 2D

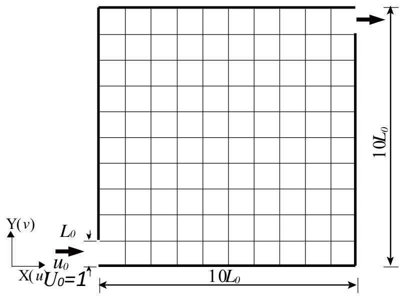


Simple room model



Industrial ventilation system (Kitchen, Push-Pull hood)

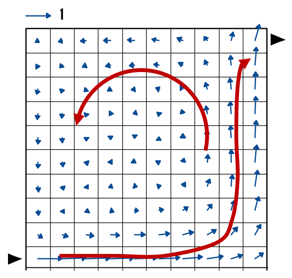
NEV and NEP analysis（2D Simple Room）



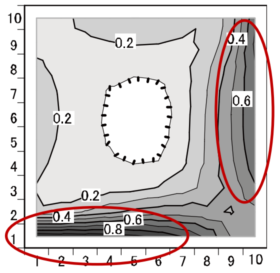
Simple 2-dimensional model

- $10L_0 \times 10L_0$ (L_0: inlet size)
- Turbulence model: standard k-ε Turbulence intensity: 30%, $Re=U_0L_0/\nu$ ≒66,000

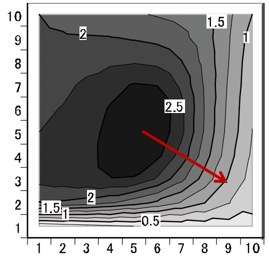
Results (flow field, diffusion field)



vector velocity

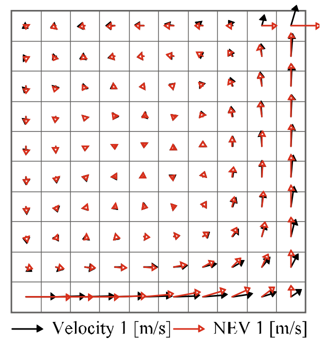


scalar velocity

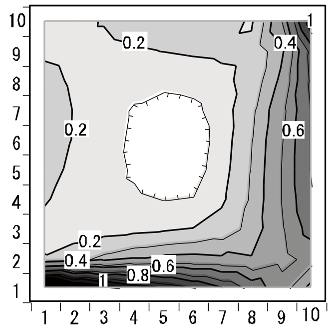


concentration

Distribution of air velocity and NEV



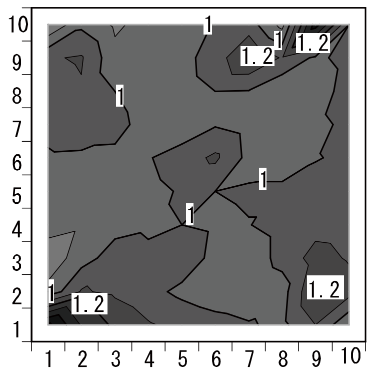
Vector distribution of NEV and U



Scalar distribution of NEV

There is no significant difference between NEV and advective velocity U. The difference is diffusion effect for contaminant transport.

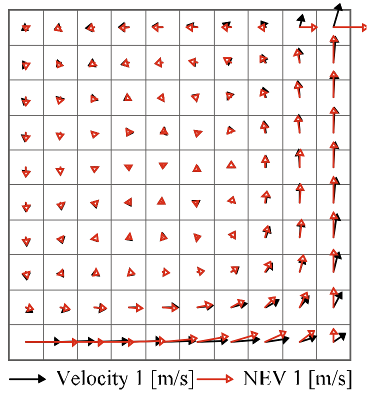
the NEV normalized by mean velocity **NEV / U**



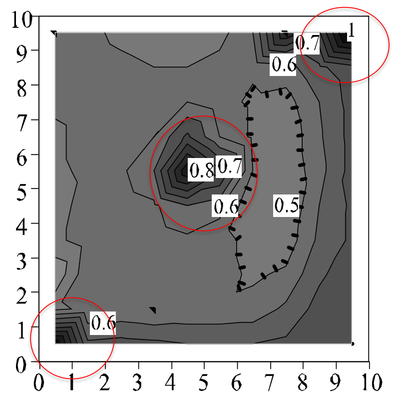
NEV / mean velocity at the CV

- Dimensionless NEV = 1, advective velocity U = NEV
- 1 The effect of the diffusion flux on the transport of contaminants
- Nondimensional NEV <1 direction: Advective velocity ≠ NEV
- Nondimensional NEV> 1 direction: Advective velocity = NEV

The distributions of advective velocity U, NEV and NEP



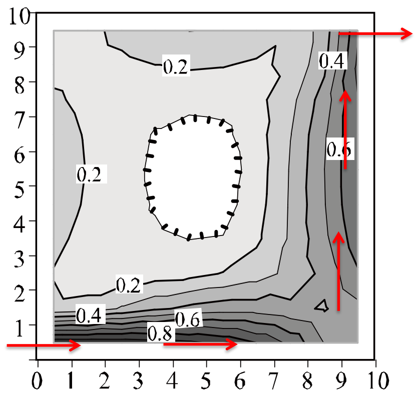
Advective velocity U and NEV



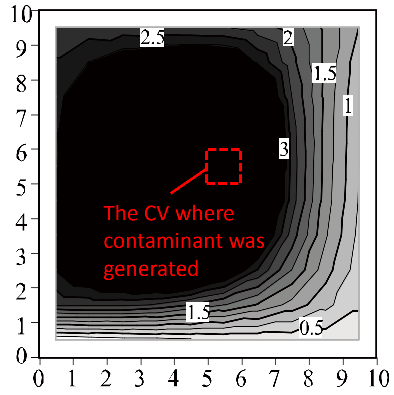
NEP

- Advective velocity ≠ NEV

Distributions

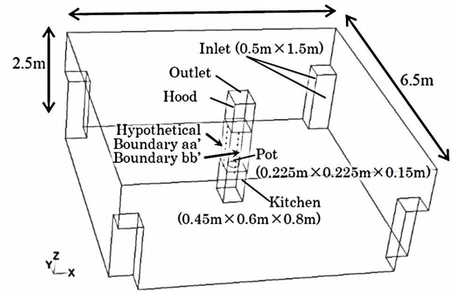


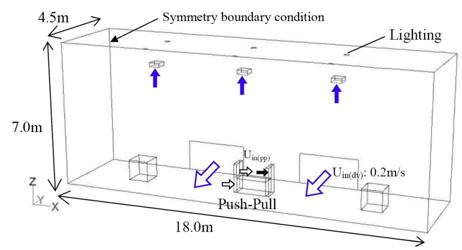
Scalar distribution of air velocity



a example of Contaminant concentration field

Application of NEV to air quality control problem for various local ventilation system

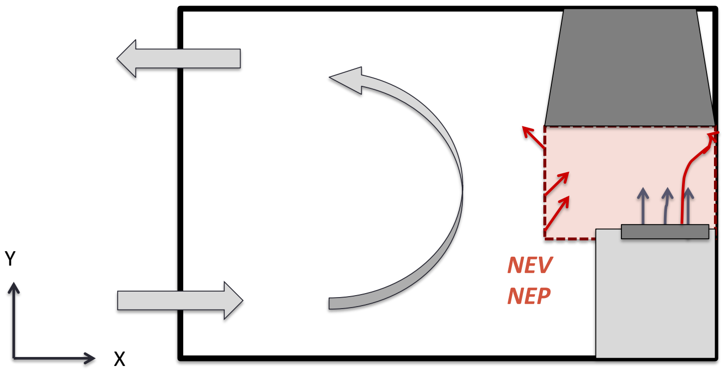




Kitchen hood

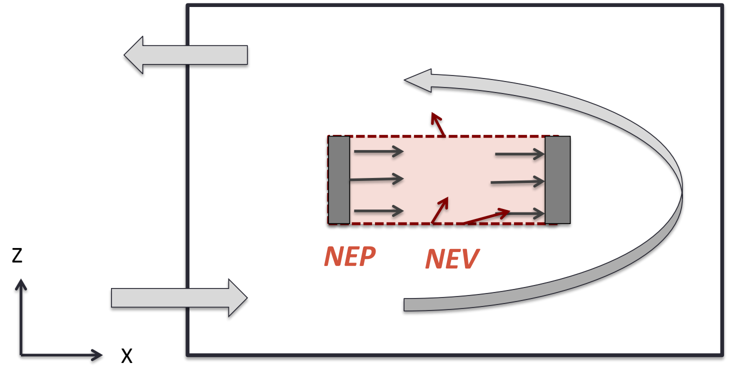
Push-Pull hood

Evaluation at the hypothetical boundaries of control zone (Kitchen hood)



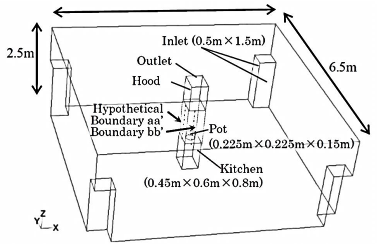
NEV* distribution on the hypothetical boundaries between the kitchen hood domain and the surrounding areas

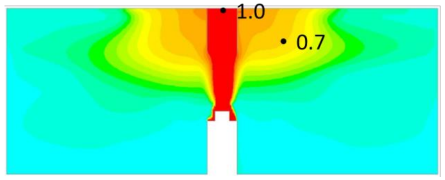
Push-Pull ventilation system



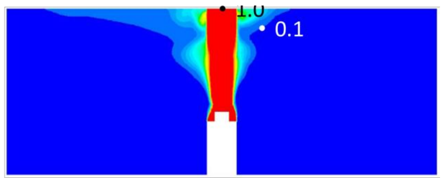
* Evaluation of ventilation efficiency by NEV and NEP on the hypothetical boundary

Kitchen hood model (different flow rate case)





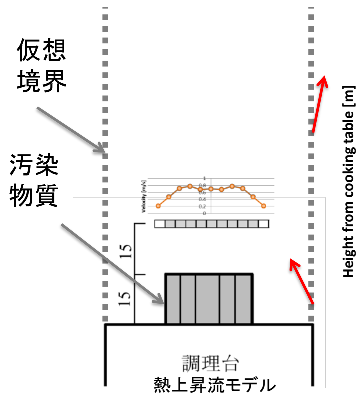
(Q_{out}: 100m^3/h)

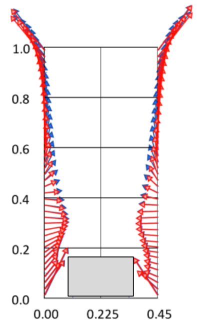


(Q_{out}: 300m^3/h)

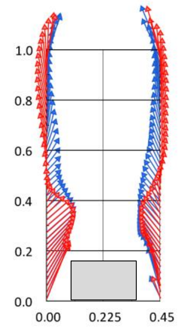
Contaminant concentration

NEV vector distribution





(Q_{out}: 100m^3/h)



(Q_{out}: 300m^3/h)

Advective velocity

NEV (Advective + diffusive velocity)

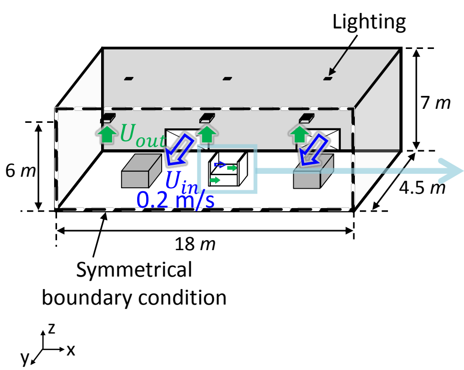
NEV and U

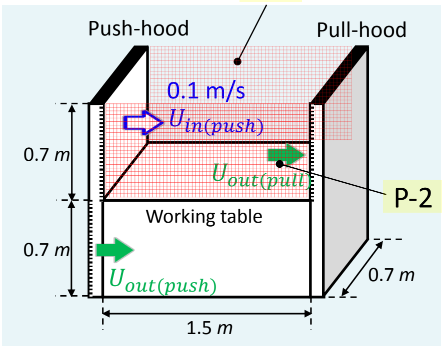
Push-Pull ventilation system model

Analysis by Dr. Chung, Kyushu University

Hypothetical boundaries of target control area P-1, P-2

Geometry of room model

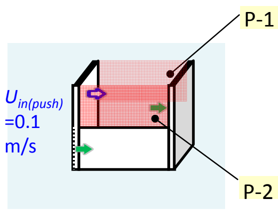




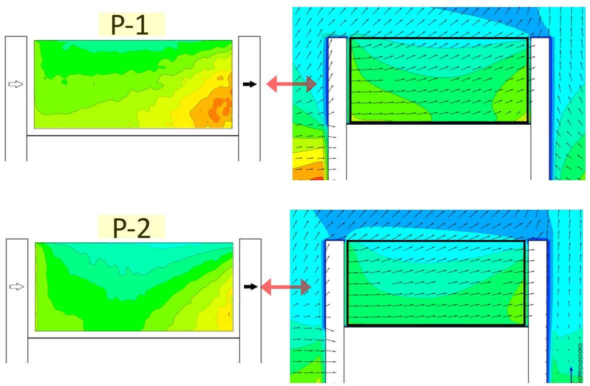
Push-pull ventilation system

NEV* distribution (Hypothetical boundary P-1, P-2)

$$NEV_x^* = \frac{1}{\phi_{CV}}\left(u_x \phi\big|_{out} - D_{eff} \frac{\partial \phi}{\partial x}\bigg|_{out} \right)$$



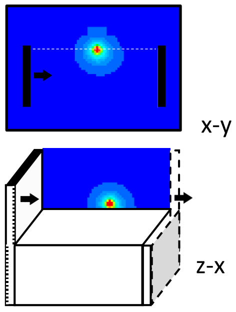
Push-pull ventilation system



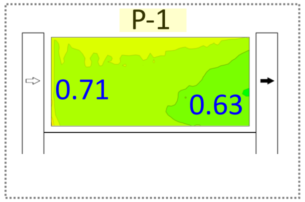
NEV* Advective + Diffusive velocity > U Advective velocity

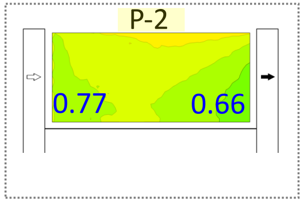
NEP distribution (Hypothetical boundary P-1, P-2)

$$NEP = \frac{qV_{CV}}{F_{outflow}A_{outflow}}$$



contaminant concentration





NEP distribution

Increasing diffusive flux flowed in the control zone

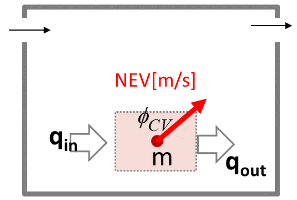
F_{inflow} ↑ ➡ NEP ↓

34~37% of contaminant is flowed to room, outside of Push-Pull control zone

Conclusion

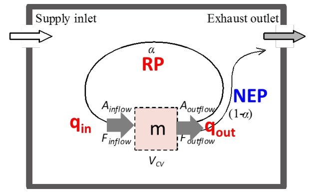
Net Escape Velocity (high value)

- The effective velocity of contaminant transport/dilution at a target point.
- Advective velocity + Diffusive velocity
- One of the limitation types of ventilation index.



Net Escape Probability (high value)

- the probability of direct exhaust of contaminant from the "point/local domain" towards the exhaust outlet
- The probability of Purging Flow Rate



Returning Probability (low value)

- The probability returning to generation point (CV) by circulating flow

Articles

- Articles concerning NEV in our article as follows,
  - Eunsu Lim, Kazuhide Ito and Mats Sandberg : New Ventilation Index for evaluating imperfect mixing condition- Analysis of Net Escape Velocity based on RANS Approach : ***Building and Environment***, 61, pp45–56, 2013
  - Eunsu Lim, Kazuhide Ito and Mats Sandberg : Performance evaluation of contaminant removal and air quality control for local ventilation systems using the ventilation index Net Escape Velocity : ***Building and Environment***, 79, pp78–89, 2014
- Articles concerning NEP
  - Eunsu Lim, Kazuhide Ito: Net Escape Probability of Contaminant from a Local Domain to Exhaust Outlet: ***J. Environ. Eng.*** 82(733), 249-256, 2017.3
  - Juyeon Chung, Eunsu Lim and Kazuhide Ito: Evaluation of Ventilation Efficiency in Local Ventilation System Based on Ventilation Indices NEV and NEP: ***J. Environ. Eng.Kyushu Branch.*** 2017.3

Conclusion

- We believe that the NEV and NEP will provide useful information to IAQ control.
- We will accumulate the analysis examples of ventilation design.

Thank you for your attention!