ESTIMATION OF HEAT TRANSMISSION THROUGH WINDOW FOR CFD SIMULATION OF INDOOR ENVIRONMENT USING VARIATIONAL CONTINUOUS ASSIMILATION METHOD

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ABSTRACT

In estimation of indoor thermal environment using computational fluid dynamics (CFD), uncertainty of boundary conditions will affect the accuracy of the estimation. In this study, the variational continuous assimilation (VCA) method was applied to estimate the boundary filed and to improve the accuracy of the CFD simulations. The method was validated by the numerical experiment, which applied the VCA method to estimation of the temperature field, flow filed, and heat transmission through the window. The experiment was performed according to the following procedure: first, the “true” temperature and flow fields were created by a CFD simulation with correct boundary conditions; second, “observation data” was extracted from the “true” temperature field; third, “initial conditions” was created by a CFD simulation without the boundary condition about heat transmission through the window; fourth, the “observation data” was assimilated into the “initial condition” by the VCA method; finally, the result of the assimilation was compared to the “true” temperature field, flow field, and boundary conditions. As a result of the experiment, it was confirmed that the VCA method could estimate the heat transmission through the window, the temperature field, and the flow field, with acceptable accuracy.

INTRODUCTION

In order to manage indoor thermal environments appropriately, it is necessary to understand temperature and flow fields. There are several methods to estimate the fields, which roughly divided into the two methods: observations and CFD simulations. Observations can obtain accurate data about temperature and flow, but it is difficult to observe whole room from the view point of observation costs. CFD simulations, on the other hand, can easily estimate temperature and flow fields, but it requires accurate boundary conditions to obtain accurate data. For the estimation of indoor thermal environments, it is difficult to set up accurate boundary conditions, because heat transmission through a window, for example, depends on the latitude, season, weather and time. In addition, there are many uncertain boundary conditions such as heating of lights, equipment, and occupants. Thus, it is worth if we can estimate accurate boundary conditions from a few observation data. In this study, a data assimilation method was used to estimate heat transmission through window from observation data.

In previous studies, many data assimilation methods were developed. Some of them were developed for estimation of indoor environment. For example, some methods performing source estimation by solving transport equation reversely(1,2,3,4,5), and other methods calculate the relationship between potential source location and observed concentration(6,7,8). Although these methods are useful for source estimation, they can not be used for the estimation of temperature and flow field because these methods assume that the accurate flow field is known. A few methods can correct flow field. Nakagawa et al.(9) used a cost function method which corrects the temperature and flow fields by minimizing the reminder of governing equations and the differences between observed values and CFD calculated values. This method, however, cannot be used for estimation of boundary conditions because the method correct temperature and flow fields directly. Sasamoto et al.(10) developed another method which calculates the contribution ratio of indoor climate (CRI) to evaluate the contribution of indoor heat factors to temperature distribution; and the CRI was used to estimate effect of each heat factor from observed air temperature. Since this method can estimate not only temperature and flow field but also boundary conditions of heat factors, it looks attractive method if there is enough calculation resource to calculate the CRI of each factor.

In this study, another data assimilation method was used. The method called variational continuous assimilation (VCA) method was developed by Derber(11), and modified by authors. The method correct CFD simulations by adding a correction term into the governing equations of CFD. The correction term can be assumed as the source term, thus the method can be used for estimation of boundary conditions. The detail of the VCA method is described in next section.

METHOD

The governing equations of the VCA method

The VCA method is a kind of 4D-VAR. The method defines an objective function, and correct CFD simulations by minimizing the function.

The objective function I of the VCA method is given by

$$I = \frac{1}{2}\sum_{p=1}^{P}\left(\Psi_{cal.}^{p} - \Psi_{obs}^{p}\right)^{\mathrm{T}}\left(\Psi_{cal.}^{p} - \Psi_{obs}^{p}\right), \quad (1)$$

where P is the number of observation steps, $\Psi^{p}_{cal.}$ and $\Psi^{p}_{obs.}$ are the vector consists of calculated and observed values at time t_p, respectively. Further, the $(\ )^{\mathrm{T}}$ notation denotes the transpose of a vector or matrix.

The corrected governing equation of CFD simulation is given by

$$\Psi_{cal.}^{n} = A^{n}\Psi_{cal.}^{n-1} + \lambda^{n}\phi, \quad (2)$$

where n means the nth calculation step, and A^n is conversion matrix acting upon Ψ^{n-1}. The matrix A^n can be obtained from the discretizing of the governing equations such as the heat conservation equation. The correction term $\lambda^n\phi$ consists of a time-dependent variable λ^n and a spatially dependent vector ϕ.

On the analogy of conservation equation, the correction term of Eq.(2) can be assumed the source term, which includes the contribution of boundary conditions.

Numerical experiment

In order to validate the VCA method applied to estimation of indoor thermal environment, a numerical experiment was performed. In the numerical experiment, simple 3D room was created as the objective room (Fig.1). The room has a window and a pair of inlet and outlet. A constant heat flux is transmitted through the window.

The procedure of the experiment is as follow: first, the “true” temperature and flow fields were created by a CFD simulation with correct boundary conditions; second, “observation data” was extracted from the “true” temperature field; third, “initial conditions” was created by a CFD simulation without the boundary condition about heat transmission through the window; fourth, the “observation data” was assimilated into the “initial condition” by the VCA method; finally, the result of the assimilation was compared to the “true” temperature field, flow field, and boundary conditions. Fig.2 shows this procedure.

In this experiment, only the heat conservation equation was corrected by adding the correction term. Flow field was corrected indirectly by re-calculating it with corrected temperature field.

Calculation conditions

The numerical experiment was performed under following assumptions: (1) temperature and flow field are steady-state conditions; (2) flow is incompressible; (3) the boundary conditions are correctly known except that of the window; (4) the “observation data” has no error.

For the CFD simulation, OpenFOAM version 2.3.0 was used. The governing equations are continuity equation, momentum conservation equation, and heat conservation equation. The buoyancy is evaluated using Boussinesq approximation because it is assumed that incompressible fluid.

The boundary conditions are shown in Table 1.

For the applying the VCA method, the variable λ^n is always 1, because steady-state condition is assumed in this experiment.

Table 1. Boundary conditions

	“true"	"initial conditions"
inlet	0.5 m/s	
outlet	Free boundary	
window	500 W/m^2	0 W/m^2

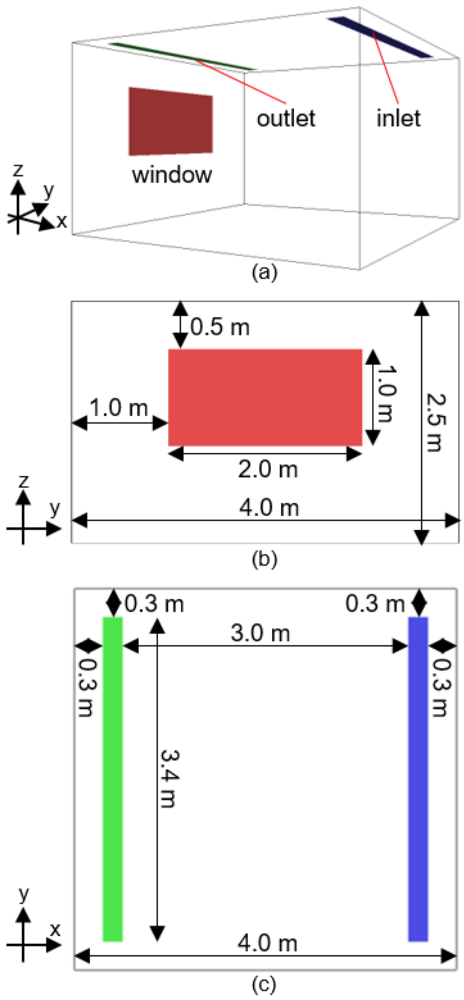

Figure 1. Objective room
(a) Bird’s-eye view, (b) elevation, (c) horizontal projection

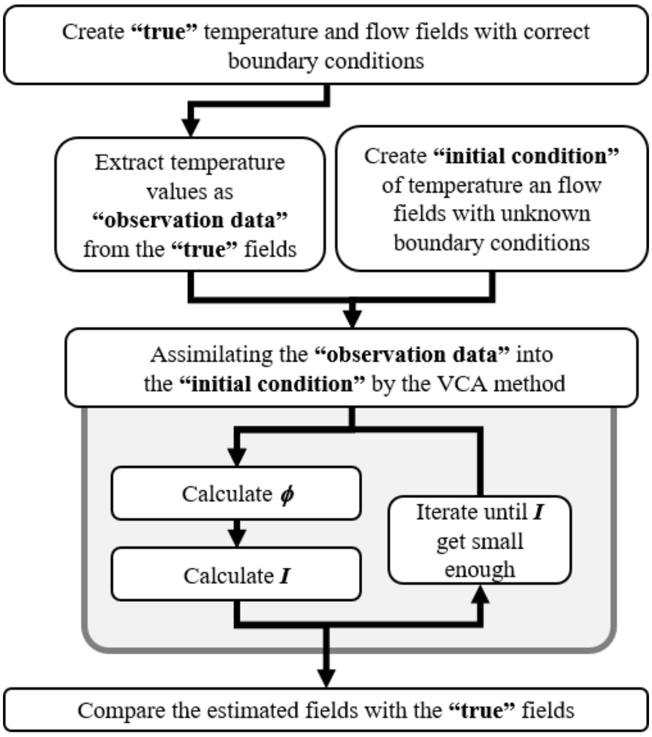

Figure 2. Procedure of numerical experiment

"True" Fields

The "true" temperature and flow fields were created by a CFD simulation with the heat transmission through the window. The results are shown in Fig.3 and Fig.4, respectively.

The heat transmission through the window makes the air temperature high, which causes the upward current forced by buoyancy near the window.

"Observation data"

In order to use it for data assimilation, the temperature distribution of the outlet was extracted from the "true" temperature field. The reason why the data of outlet was used for data assimilation is that the data to use the VCA method should be located on the leeward of the source(5).

In this numerical experiments, it was assumed that the "observation data" has no error.

"Initial condition"

The "initial condition" was also created by CFD simulation with no heat transmission through the window. The flow field is shown in Fig.5. The figure of temperature field is omitted because there is no heat source in the "initial condition" and the temperature is uniformly 300 K.

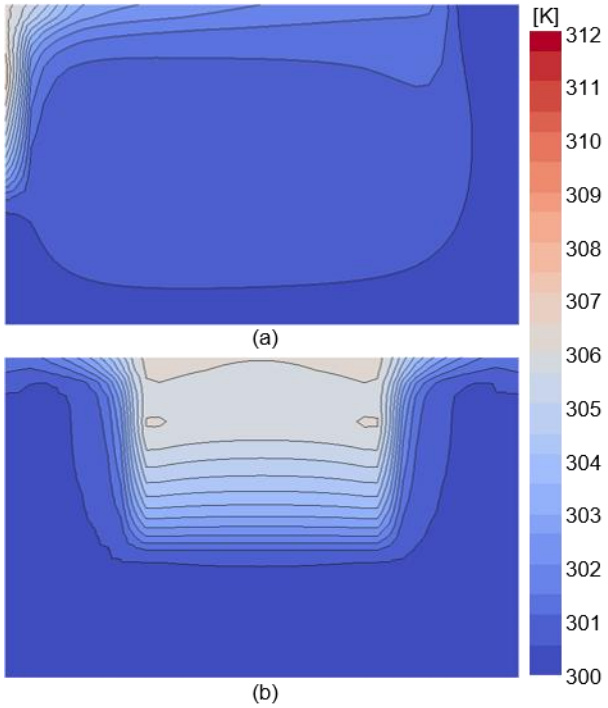

Figure 3. The "true" temperature field
(a) y=2.05 m, (b) x=0.05 m

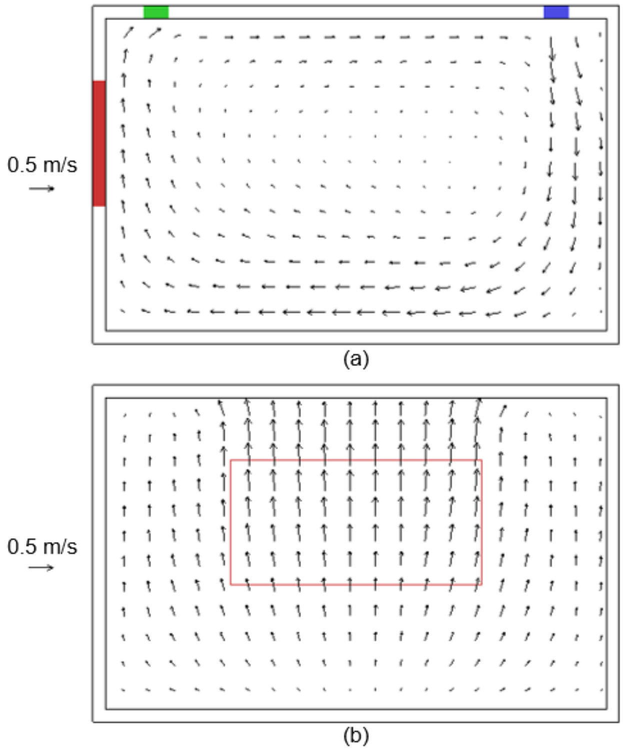

Figure 4. The "true" flow field
(a) y=2.05 m, (b) x=0.05 m

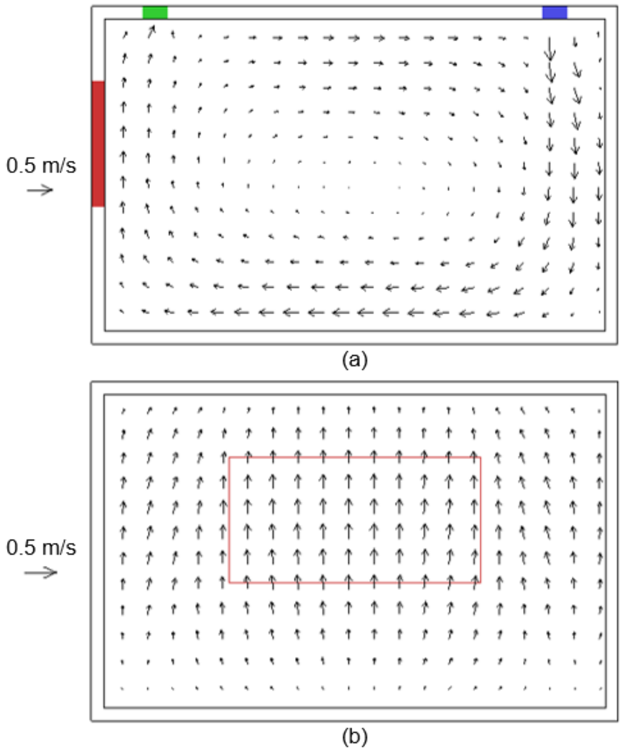

Figure 5. The flow field of "initial condition"
(a) y=2.05 m, (b) x=0.05 m

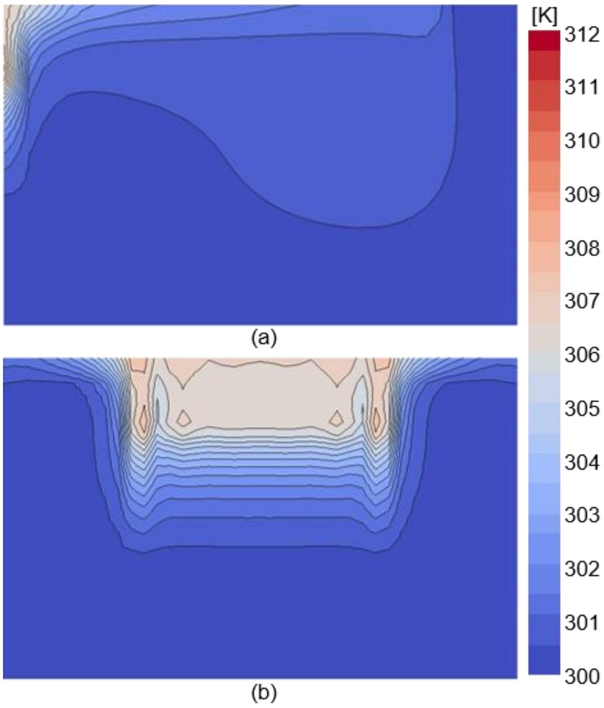

Figure 6. The estimated temperature field
(a) y=2.05 m, (b) x=0.05 m

RESULTS AND DISCUSSIONS

The VCA method was applied to assimilate the "observation data" into the "initial condition" in order to estimate the "true" temperature and flow field, and the amount of the heat transmitting through the window.

The estimated temperature and flow fields are shown in Fig.6 and Fig.7, respectively.

Fig.6 shows that the VCA method overestimates the temperature field at the upper side of the window, and underestimates at the lower side. This result indicates that the correction of the VCA method exists at which closer to the observation data.

Fig.7 shows the upward current forced by the heat transmission through the window. This indicates that flow field also corrected by the VCA method, indirectly.

The estimated heat transmission through the window is shown in Fig.7.In the upper side of the window, the heat transmission is overestimated, and in the lower side, it is under estimated.

In addition, on the right and left edge of the window, the large values exist. Since the outlet where observation data is located is broader than the window, the edge of the window receives the contribution of not only the observation data located upward, but also the observation data located left or right side of outlet.

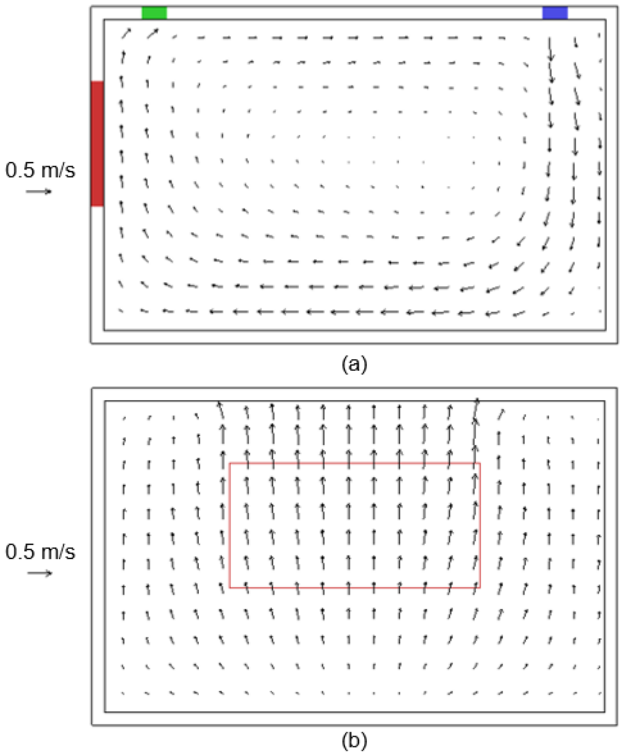

Figure 7. The estimated flow field
(a) y=2.05 m, (b) x=0.05 m

Figure 8. Estimated heat transmitting through the window

The sum of the estimated heat transmission is about 964 W. It is slightly underestimated than the correct heat transmission through the window (1000W).

The RMSE values of the temperature and flow field are shown in Fig.9, 10. The values are defined by Eq.(3) and Eq.(4), respectively.

$$RMSE_{temp.} = \sqrt{\frac{1}{N}\Sigma\left(T_{est.} - T_{true}\right)^2} \tag{3}$$

$$RMSE_{flow} = \sqrt{\frac{1}{N}\Sigma\left(U_{est.} - U_{true}\right)^2} \tag{4}$$

where N is the number of calculation cells. $T_{est.}$ and $U_{est.}$ are the values of the "initial conditions" or the values estimated by the VCA method. T_{true} and U_{true} are the "correct" values.

Fig.9 and Fig.10 show the RMSE values calculated for "initial condition", and the result of the VCA calculation, about all the calculation cells of the objective room, and the cells on the window, respectively. In Fig.9 and Fig,10, the RMSE values of the result of the VCA calculation are much smaller than that of the "initial condition". This result confirms that the VCA method can improve the accuracy of the simulation. The RMSE values of the cells on the window, however, are not reduced as much as that of whole room. This result may be caused by un accuracy of the distribution of the correction term. Although the error is smaller at the place far from the window such as outlet, the error is larger at the place near the window. Thus it can be said that the observation points should be located close enough to unknown boundary conditions in order to detect the error with high accuracy.

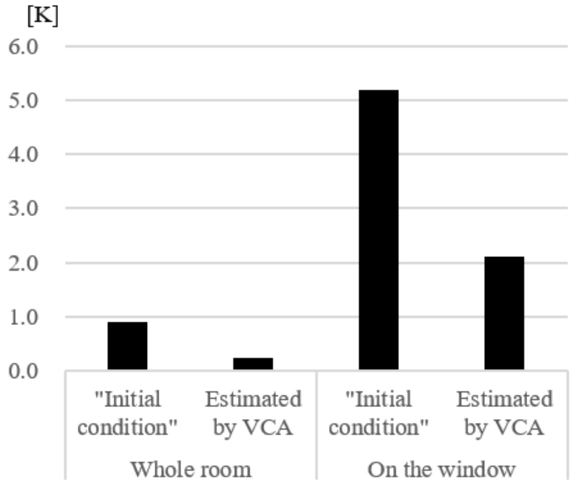

Figure 9. RMSE values of the temperature

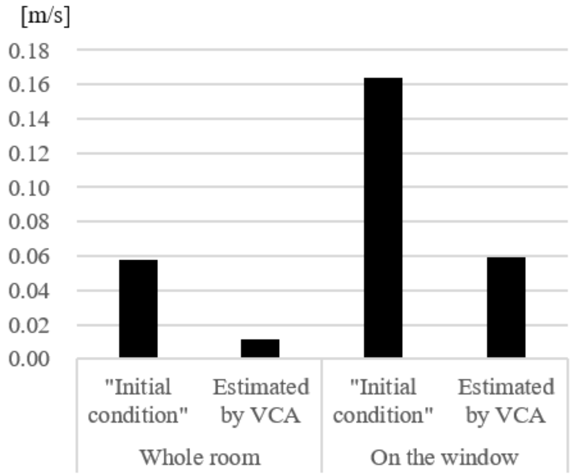

Figure 10. RMSE values of the velocity

CONCLUSIONS

In this study, the VCA method was applied to estimate the heat transmission through the window, temperature field, and flow field. In order to validate the method, a numerical experiment was performed according to the following procedures: first, the "true" temperature and flow fields were created by a CFD simulation with correct boundary conditions; second, "observation data" was extracted from the "true" temperature field; third, "initial conditions" was created by a CFD simulation without the boundary condition about heat transmission through the window; fourth, the "observation data" was assimilated into the "initial condition" by the VCA method; finally, the result of the assimilation was compared to the "true" temperature field, flow field, and boundary conditions.

As a result of the experiment, it was confirmed that the VCA method could estimate the heat transmission through the window, temperature and flow field with acceptable accuracy.

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