Optimization of Hybrid Air-conditioning System with Natural Ventilation by GA and CFD

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ABSTRACT

This study aims at the development of an optimal design tool using a genetic algorithm (GA) and computational fluid dynamics (CFD). To represent a realistic building environment, random variables (fluctuating outdoor conditions), passive control variables (model variables) and active control variables (HVAC system) were set up. A combination of designs are determined based on the relationship between the fluctuating outdoor conditions and the HVAC system in the optimization inquiry. Building environment design should consider this relationship of active and passive control because the HVAC system works until the indoor climate reaches the target indoor climate when outdoor conditions are changing.

Keywords

Optimization, Genetic Algorithm (GA), Computational Fluid Dynamics (CFD)
Passive and active control elements, Random variables, Feed-back loop

1 Introduction

This study aims at the development of an optimal design tool using GA and CFD [2], [3], [4] for hybrid air-conditioning [1]. As elements to be considered in the design, there are the outdoor condisions, passive control elements for natural wind forced ventilation (such as the form of the inside and outside of the building), and active control elements of the indoor environment (such as HVAC system). Outdoor conditions are a fluctuating factor, and active control elements of the indoor climate (such as HVAC system) which are changing the output (boundary conditions of HVAC) in order to maintain the indoor climate at the target level for fluctuating outdoor conditions. This research treats the outside conditions as random variables, and examins the design variables selected by GA and actively changes the indoor situation corresponding to the outdoor conditions with a feed-back loop from the outputs of HVAC system control to the input boundary conditions of the CFD. This optimization method means that the feed-back loop of sensor and outputs of HVAC works until indoor climate is at the target level after GA has selected passive elements (design variables). The whole process of optimization consists of a two-step process to reduce the calculation load for finding the optimal solution. This study carried out a simple analysis using a coarse mesh considering the calculation load in the first step. In the second step, a detailed CFD analysis using a fine mesh was performed on the cases ranked top selected in the first step.

2 Optimization method Using GA and CFD

2.1 The optimization method

1. Setting up passive control elements for natural ventilation (design variables), active control elements (such as HVAC system), random variables (here mainly climatic conditions), restricting conditions and the objective function.

2. Design variables are selected by an optimization technique, and random variables are seleceded by a sampling technique.
3. CFD analysis is performed on the selected design variables and the selected random variables.
4. Active control elements are changed by the CFD feed-back loop, and the indoor climate is analyzed until it reaches the target value.
5. Restricting conditions and the objective function are evaluated.
6. Repeat loops 2-5 and the cases selected from the top rank which show a high value for the objective function in the first step.
7. In the second step, a detailed CFD analysis is performed on the selected cases.

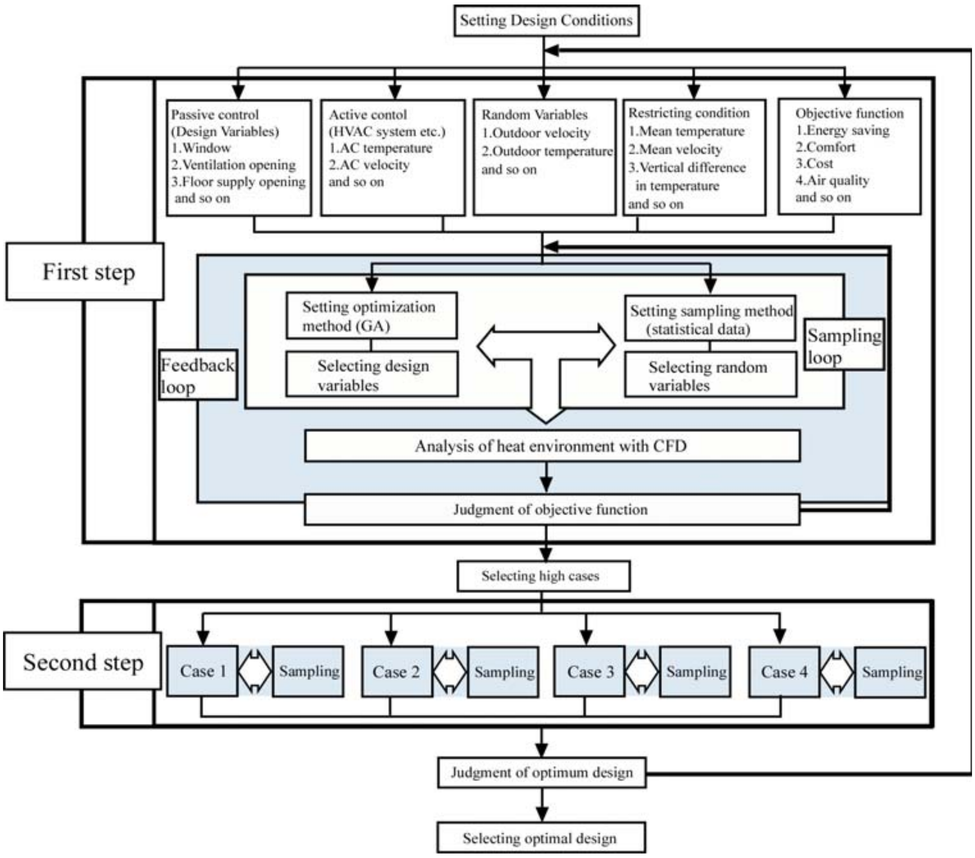


Fig. 1 The optimization procedure

3 Optimization Design Case Study

Assuming that the outdoor temperature is the changing factor, optimization is performed on a hybrid air-conditioning system [1] with natural ventilation in the mid-term.

3.1 Basic Model

The basic model for this study is shown in Figure 2 and Table 1. The width of the calculation area is set at half of the 3.6 m office module (1.8 m), considering of the symmetrical configuration. Hybrid air-conditioning is modeled as the outdoor air flows into the room from the upper opening of the window (0.5×1.8 m; Fig. 2, left), and is expelled through the opening at the other side (0.5×1.8 m; Fig. 2, right), while the HVAC is still operating. And the floor supply openings (0.1×0.2m) are set up. An I-shaped partition and a desk are installed. Personal computers and a human model are installed to represent the source of internal heat generation. In this study, The HVAC system in the room is assumed to be operating and the output of the HVAC is controlled by the CFD feed-back loop.

3.2 Design variables

Design variables for this study are shown in Figure 3. In this study, three design pattern elements are examined for the hybrid air-conditioning system with natural ventilation. These are the locations of the floor supply openings (6 patterns), the styles of the natural ventilation supply openings (5×5=25 patterns, there are two design variables which are width and height of the natural ventilation) and the styles of the window (5×(2×12-1)=115 patterns, there are three design variables which are the width and height of the window and the window start line which are 0.8 m and 2.0 m). The total number of design patterns is 17250.

3.3 Random variables

This study considers only the outdoor temperature which is based on the weather data of the Japan Meteorological Agency from May to June. The wind induced ventilation rate is assumed to be constant with the device of constant volume. The data for the random variables are selected by taking one hour intervals from 8:00 to 18:00. The moment design method was used for selecting random variables according to the average changes in the distribution and standard deviation of the outdoor conditions in this study, and on the assumption of instantaneous diffusion conditions without considering the influence of thermal storage in the building structure. The probability of a random variable is used as a weighting factor, which is multiplied by the objective function. The statistical value of the objective function is calculated with changing outdoor conditions taken into account. In this study, only the range $\pm 2\sigma$ (95.4% of the entire ranges) is based on the mean value (M) of the outdoor temperature. The sampling interval and random variables are shown in Table 2.

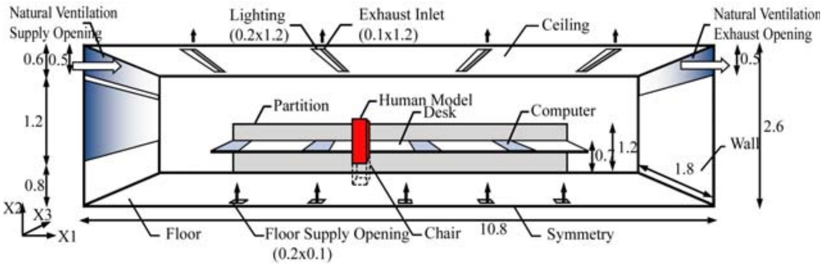


Fig. 2 Basic model (Units:m)

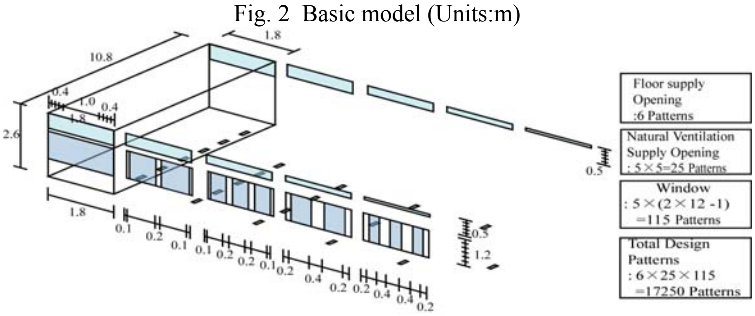


Fig. 3 Design variables (Units:m)

Table 1 Heat sources (Basic model)

Heat sources	Solar Heat (Window)	Lighting (4 Units)	Computer (4 Units)	Human model (One body)	floor four human bodies	Total
Quantity of heat	100W/m^2	400W	800W	55W	220W	1700W
・Floor area of 19.4 m^2 produces 88 W/m^2 of sensible heat ・Human model is a cube of dimensions 0.45m×0.33m×0.88m						

Table 2 Random variables

Sampling interval	Probability	Random variable (ºC)
-2σ — -σ	0.136	20.95 (M−1.5σ)
-σ — M	0.341	21.94 (M−0.5σ)
M — σ	0.341	22.93 (M+0.5σ)
σ — 2σ	0.136	23.92 (M+1.5σ)
Mean value(M) = 22.43 ºC, Distribution (σ^2) =0.977 ºC, Standard deviation (σ) = 0.99 ºC		

4 Setting the Optimal Design

4.1 Objective function

The single objective function is the amount of energy-input to the HVAC system. The objective function is as follows:

$$E(kW) = Cp \times \rho \times \Delta T \times Q \qquad (1)$$

Cp: Constant-pressure ratio heat of air [J/kg·K], ρ: Density of air [kg/m^3]
ΔT: Difference in temperature on outflow and inflow temperature of HVAC system [K]
Q: The amount of wind on inflow of HAVC system [m^3/s]
The optimal evaluation is achieved when the amount of energy-input in equation (1) reaches a minimum.

4.2 Restricting conditions

The restricting conditions set for the indoor environmental design in this study are as follows:
·The target temperature is 26.0ºC (±0.2ºC)in the task region.
·The size of window is over than 2.8m^2 a seventh of floor area.
·The average wind velocity is below 0.5 m/s in the task region.
·The limit wind velocity is below 2.0m/s on floor supply opening.
·The vertical difference in temperature is below 3.0ºC in the task region.
Here, the task region is X_1=0.9-10.8 m, X_2=0.0-1.5 m, and X_3=0.0-1.8 m. The number of air changes per hour for the natural ventilation is fixed at 10 times, and the floor supply openings are fixed at 19 ºC.

4.3 GA and CFD analysis conditions

A multi-island genetic algorithm [4] is used in the first step for optimization. The detailed setup is shown in Table 4 and the boundary conditions of the CFD are shown in Table 5. The flow field is analyzed with three-dimensional CFD based on a standard k-ε model.

Table 4 Setting the multi– island GA

Size of Sub-Population	10
Number of Islands	4
Number of Generations	10
Rate of Crossover	0.8
Rate of Mutation	0.1
Rate of Migration	0.5
Interval of Migration	3
Total	400 (10×4×10) × 4 (Sampling)=1600

Table 5 Boundary conditions for the CFD simulation

INLET	$K_{in} = 3/2\,(U_{in} \times 0.05)^2$, $\varepsilon_{in} = C_\mu^{3/4} \times k_{in}^{3/2} / l_{in}$ l_{in} = One seventh of the opening width U_{in}: Velocity of inflow (m/s), C_μ= 0.09
OUTLET	U_{out}: Mass balanced, Tout, kout , ε_{out} : Free slip
Wall,human model	Generalized log-law (Wall Function), Free slip at symmetric plane. Heat flux of human body and floor is fixed.
Turbulence model	High reynolds number k-ε model
Difference scheme	First-order upwind difference
Mesh	1st step 55(X_1)×25(X_2)×16(X_3)= 22000 2st step 78(X_1)×35(X_2)×22(X_3)= 72000
k : kinetic energy of inflow [m^2/s^2], ε: kinetic energy dissipation rate [m^2/s^3], in: inlet out: outlet , T: temperature [K], U: velocity of inflow [m/s], l: specific length scale [m]	

4.4 Feed-back loop

The HVAC system is set so that a sensor is in agreement with the target temperature until the indoor temperature reaches 24 ºC (Heating) and 26 ºC (Cooling) in the hybrid air-conditioning model room with the feed-back loop of CFD. It is set so that the AC supply temperature is 19 ºC for cooling and 26 ºC for heating. The amount of supply air is controlled.

4.4.1 The convergence evaluation standard of the feed-back loop

a) Cooling : The mean temperature in the task region is 26 ºC (The accuracy is less than ±0.2 ºC).
b) Heating : The mean temperature in the task region is 24 ºC (The accuracy is less than ±0.2 ºC).
c) None HVAC system: The amount of HVAC supply air is 0 ($Q<0.001m^3/s$). When the mean temperature is 24ºC-26ºC in the task region with the amount of supply air which is 0.001 m^3/s.

4.4.2 The standard for changing the HVAC setting between cooling and heating in the feed-back loop

a) Changing from cooling to heating: Even if the amount of supply air (Cooling) is set to 0 ($Q< 0.001m^3/s$), when the mean temperature of a task region is less than 24ºC.
b) Changing from heating to cooling: Even if the amount of supply air (Heating) is set to 0 ($Q< 0.001m^3/s$), when the mean temperature in the task region is more than 26 ºC.

4.4.3 The detailed feed-back loop

$Q_{NEW} = Q_{OLD} + \Delta Q$

$\Delta Q = [(T_{TASK} - T_{TAGET}) \times V_{TASK}]/[(T_{TASK} - T_{SUPPLY}) \times t(s)]$

Q_{NEW} = The modified amount of wind [m^3/s]. Q_{OLD} = The amount of wind before modifying[m^3/s].
ΔQ=The up and down amount of wind [m^3/s]. T_{TASK} = The mean temperature of task region [ºC].
T_{TAGET} = The target temperature of the HVAC system[ºC]. V_{TASK} = The volume of task region[m^3].
t = The relaxation time [s].

5 Simulation Result

5.1 GA and CFD analysis conditions

The results of the optimal design in the first step by multi-island GA and CFD are shown in Figure 4. The top three cases are selected in the first step for a detailed CFD analysis using a

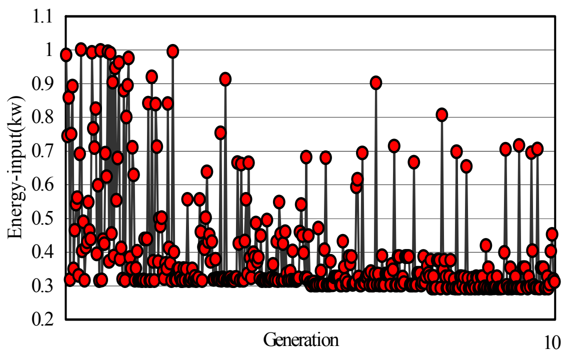


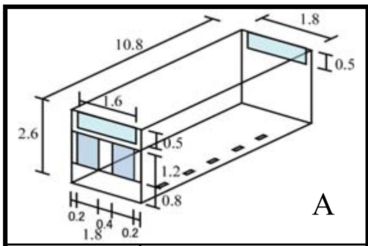
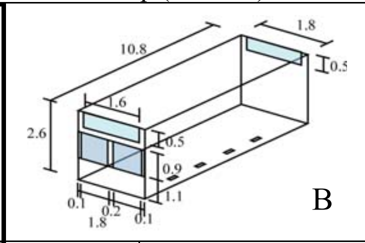
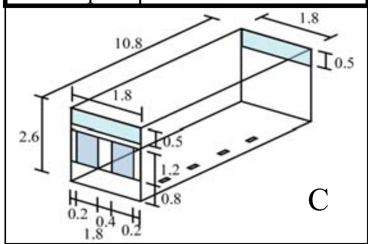
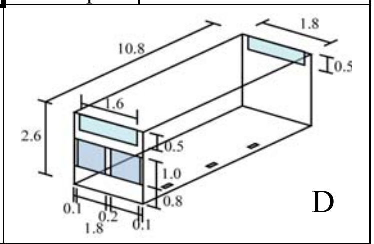
Fig. 4 Curve of GA inquiry

fine mesh in the second step.

5.2 The design selected in the first and second step

The design selected in the first step is shown in Table 6. The simulation result shows that the objective function is low when a larger natural ventilation opening is selected. It is assumed that the amount of sensible heat removal increases when the natural ventilation opening becomes larger. The floor supply openings are selected according to the relationship between the natural ventilation opening and the window. When the natural ventilation opening becomes small, there is a tendency for the number of floor supply openings to increase. And the amount of energy-input increases when the outside temperature becomes high. In this study, Case A where the purpose function is the highest in step 2 search serves as the optimal design. The CFD analysis results of Case A are shown from figures 5 to 8.

Table 6 Cases selected in the first step (Unit:kw)

			
1Step	0.290	1Step	0.290
2Step	0.300	2Step	0.301
			
1Step	0.291	1Step	0.292
2Step	0.301	2Step	0.302

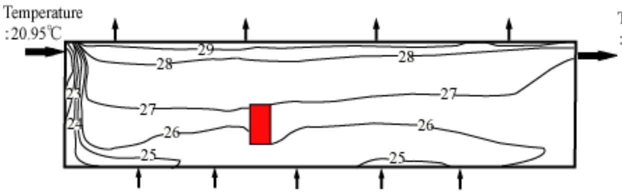


Fig.5 Temperature field (Section,Outdoor:20.95ºC)

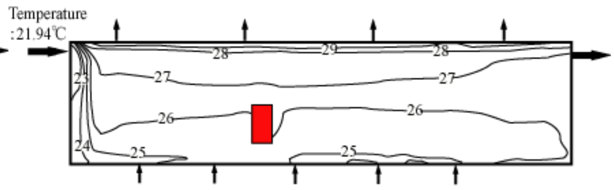


Fig.6 Temperature field (Section,Outdoor:21.94ºC)

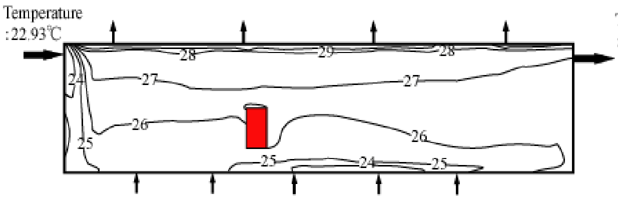


Fig.7 Temperature field (Section,Outdoor:22.93ºC)

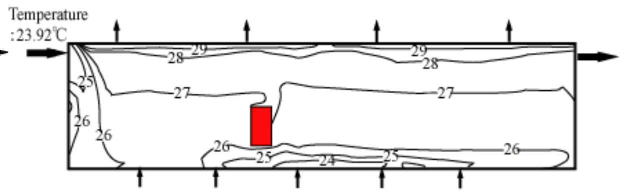


Fig.8 Temperature field (Section,Outdoor:23.92ºC)

6 Conclusions

A hybrid air-conditioning system with natural ventilation in the mid-term was investigated as an example of the optimal design.

The optimal inquiry based on fluctuating factor outdoor conditions as the random variables, the building form as the passive control, and an HVAC system as the active control was performed, and its validity was demonstrated.

A two-step inquiry using a genetic algorithm showed that it was possible to produce an optimal design with a reduction in the calculation time.

The energy-saving effect of the hybrid air-conditioning system using natural ventilation in the mid-term was clarified.

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