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(Title) **A STUDY OF WINDOW LOCATION AND FURNITURE LAYOUT TO MAXIMIZE THE COOLING EFFECT FOR AN URBAN TAIWANESE APARTMENT BY NIGHT VENTILATION**

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SYNOPSIS

The year-round climate of Taiwan is warm and humid. Apart from the hottest months in summer, there are four months suitable for nocturnal ventilation to acquire indoor cooling. The urban Taiwanese apartments are small due the limited usable land. To maximize the spatial use, a relative large occupant-defined space is developed. This space can be divided into two to three sub-spaces with wall units or smaller pieces of furniture when needed. Based on a previous study in a typical occupant-defined space, some wintertime design principles of furniture layout to achieve high indoor air quality were obtained. To provide an overall picture of the natural ventilation design for such a space, this study investigates the impacts of window location and furniture layout on the summertime indoor thermal comfort and air quality by night ventilation. Different furniture layouts have neglected effects on indoor thermal comfort when the layout does not obstruct the primary supply air stream. More spatial divisions by wall units can help to removal CO_2 effectively by minimizing mixture among stratified thermal layers. Lower window location makes the penetration of supply air stream deeper into the room, which results in a cooler region away from the window. Lower window location achieves lower indoor CO_2 concentration level than higher window location.

INTRODUCTION

The subtropical climate of Taiwan is warm and humid. Apart from the hottest two months (July and August) of which the monthly average temperatures are over 28°C, there are four months the monthly average temperature are between 24°C and 28°C. During these months the daily temperature difference between the highest and lowest is around 6°C. For energy conservation, nocturnal ventilation could be a potential strategy for acquiring indoor cooling.

Due to limited usable land, the urban Taiwanese apartments are small. To maximize the utilization, a relative large space, called occupant-defined space, is developed. The occupant-defined space can be divided into two to three sub-spaces with wall units or smaller pieces of furniture when needed. It is important for designers to know how to arrange furniture in accordance with window locations to maximize the cooling effect and obtain high indoor air quality from night ventilation.

From a previous study [Chao et al. 1997] some design principles to sub-divide an occupant-defined space by wall units were obtained to achieve high indoor air quality in winter. High indoor air quality can be obtained if wall units can be arranged to be kept away from the primary air flow path. By studying the air flow pattern of a typical occupant-defined space two suggestions were made. To make the air circulate freely in a space, a gap should be left at the bottom of each wall unit. The height of a wall unit should be restricted when the wall unit is beside a heat/pollutant source, simulating a person. The heat/pollutant source can hardly be reached by the supply air stream if the wall unit is too high.

To provide an overall picture of the natural ventilation design for a typical occupant-defined space, this study examines the summer indoor thermal comfort and air quality when night ventilation is applied The goal of this study is to maximize the nocturnal cooling effect by investigating the impacts from both of window location and furniture layout on indoor thermal comfort and air quality.

RESEARCH METHODS

CFD simulations

This study was carried out by computational fluid dynamics simulations. Since thermal buoyancy effect is prominent in this study, the applied turbulence model is the renormalization group k-ε model [Yakhot et al. 1992]. It has been found that the renormalization group k-ε model is more advanced in predicting the thermal buoyancy effect than the standard k-ε model and the modified k-ε model [Chen and Chao 1996]. The renormalization group k-ε model has the same form as the standard k-ε model, except for the model coefficients. The model coefficients in the renormalization group k-ε model are:

$$(\delta_k, \delta_\varepsilon, C_{1\varepsilon}, C_{2\varepsilon}, C_\mu) = (0.7194, 0.7194, 1.42, 1.68, 0.0845) \tag{1}$$

In addition, the dissipation-rate transport equation has an additional source term R:

$$R = \frac{C_\mu \eta^3 (1 - \eta/\eta_0)}{1 + \beta\eta^3} \frac{\varepsilon^2}{k} \tag{2}$$

where $\eta_0 = 4.8$, $\beta = 0.012$ and the dimensionless parameter, η, is defined by:

$$\eta = S\frac{k}{\varepsilon}, S = (2S_{ij}S_{ij})^{1/2}, S_{ij} = \frac{1}{2}(U_{i,j} + U_{j,i}) \tag{3}$$

The computations are conducted by PHOENICS [Spalding 1994], a commercially available CFD code, which is popular among ventilation engineers. The governing equations are solved in the finite-volume method with a staggered grid system. A hybrid scheme is used for the numerical solution. The algorithm employed is SIMPLEST [Spalding 1994]. As a convergence criterion, the sum of the normalized absolute residuals in each control volume for all calculated variables should be maintained at less than 10^{-3}. To prevent the numerical solution process from oscillating or diverging, three methods are used. They are under-relaxation for the continuity equation, false time-steps for the other dependent variables, and source-term manipulation which treats positive source terms explicitly and negative source terms implicitly. A non-uniform mesh system is used with the finer mesh located in the near-wall region or the place with a large gradient of variables.

Apartment unit

A typical occupant-defined space was chosen from an apartment unit (Fig. 1) located in an apartment complex in Taipei. The left side of this apartment unit, denoted by dash line, is the occupant-defined space (Fig. 1). Three kinds of window locations and three types of spatial division were investigated (Fig. 2). Case B and C were chosen because of their good performance in obtaining high indoor air quality by the effective removal of CO_2 [Chao et al. 1997]. Three lying persons, each generating 75 w of heat and 4 x 10^{-6} m^3/s of carbon dioxide (CO_2), were simulated. The room and wall temperatures are 30°C which are considered to be 4°C higher than the outdoor temperature (26°C). The simulation cases and the corresponding dimensions are shown in Table 1 and Table 2. All simulations were conducted in three dimensions in 39 x 20 x 23 cells.

Evaluation models
To assess the performance of each design option, the average indoor thermal comfort and the average indoor concentration of CO_2 are evaluated. Indoor thermal comfort is evaluated on both Fanger's Predicted Mean Vote [Fanger 1982] and his draft risk model [Fanger et al. 1988]. The Predicted Mean Vote is determined by three personal parameters and four environmental parameters. The three personal parameters are metabolism, external work, and clothing insulation. The four environmental parameters are air temperature, mean radiant temperature, mean air velocity, and partial water vapor pressure. The draft risk model is a function of mean air velocity, turbulence intensity, and air temperature. To obtain a 90% level of satisfaction in thermal comfort, the value of the PMV should be kept between -0.5 and +0.5. A 15% or lower level of dissatisfaction in draft risk is desirable. Indoor air quality is evaluated on the average pollutant concentrations in three zones. A lower pollutant concentration in the evaluated region indicate an effective removal of CO_2. Six regions, two regions in each zone, are chosen for evaluating indoor thermal comfort and air quality. The location for each region is shown in Fig. 2.

RESULTS AND DISCUSSION

From Table 3, 4 and 5 one can find that thermal comfort level around each heat/pollutant source (zone 1) for all 9 cases is similar. The thermal comfort levels in region 1 of three zones for all cases are higher than 0.5, the comfort level, which means warm in the space. The percentages of dissatisfaction due to drafts in six regions for all cases are well below 15%, a desirable criterion.

Furniture layout
In this study different ways of spatial division by wall units have neglected effects on indoor thermal comfort level. The possible explanation is that the arrangement of wall units in case B and case C does not obstruct the air circulation in the whole space [Chao et al. 1997]. For each wall unit there is a gap left at the bottom to make the supply air stream go deeper into the space. In addition, the wall unit #1 and #3 are made shorter to make air circulation easier.

Different layouts of wall units have prominent influences on the ease in removing CO_2. Case C, the case with three wall units, obtains the lowest indoor CO_2 concentration level comparing with case A and B. The same situation has been found in the previous study in which less supply air volume was considered [Chao et al. 1997]. The possible explanation is that wall units are help to prevent mixture among different stratified thermal layers. The stratified thermal layers are generated by thermal buoyancy effect. More mixture among different thermal layers makes the removal of CO_2 difficult and consequently, results in a high indoor CO_2 concentration level.

Window location
Type 1 window location (case A-1, B-1 and C-1) can make the supply air stream penetrate deeper into the room comparing with higher window locations. This situation can be observed from all three cases in Table 3 in which the PMV value is relatively lower in zone 3 than in other zones. The higher the window the shorter the penetration depth is. Therefore, type 3 window location (case A-3, B-3 and C-3) has the lowest PMV value in zone 1 than in other zones.

The higher the window location, the higher the indoor CO_2 concentration level will be. Type 1 window location obtains the lowest CO_2 concentration level than the other types. The reason is that the position of type 1 window is lower the heat/pollutant sources. Type 2 window location is at the same level of the heat/pollutant sources while type 3 window location is higher than the heat/pollutant sources. Since the thermal buoyancy effect is dominant around the heat/pollutant sources, a lower window location (lower than the heat/pollutant sources) helps to preserve the stratified thermal layers generated above the heat/pollutant sources. By preserving the stratified pattern, the indoor CO_2 can be removed effectively. The weakness of higher window location can somehow be adjusted by the gap beneath a wall unit. As one can observe from Table 3, 4, and 5, the difference in CO_2 concentration between case C and the other two cases increases with a raising window location. This situation states that the gap left beneath each wall unit regulates the supply air stream to reach the heat/pollutant source at a lower level, which helps to preserve the stratified thermal layers pattern.

CONCLUSION

This study investigate the impacts of furniture layout and window location on indoor thermal comfort and air quality by night ventilation. It was found that different ways of spatial division by wall units have neglected effects on indoor thermal comfort if the layout does not obstruct the primary supply air stream. Since thermal buoyancy effect is the dominant force around the heat/pollutant sources, more spatial divisions by wall units can minimize the opportunity of mixture among stratified thermal layers, which makes the removal of CO_2 effectively. Lower window location makes the penetration of supply air stream deeper into the room, which results in a cooler region away from the window. The higher the window location the less penetration depth can be made. Thus, higher window location brings more cooling effect in the area close to the window than the area far away. Lower window location, lower the heat/pollutant sources, achieves lower indoor CO_2 concentration level than higher location for the thermal buoyancy effect is prominent around the sources. It was also found that the cooling effect by a 5 ach supply air volume at 26^oC is not enough for a room with a 30^oC wall temperature and three heat sources, each with 75W. Further study is needed to identify the proper season and supply air volume to provide indoor thermal comfort by night ventilation.

ACKNOWLEDGMENTS

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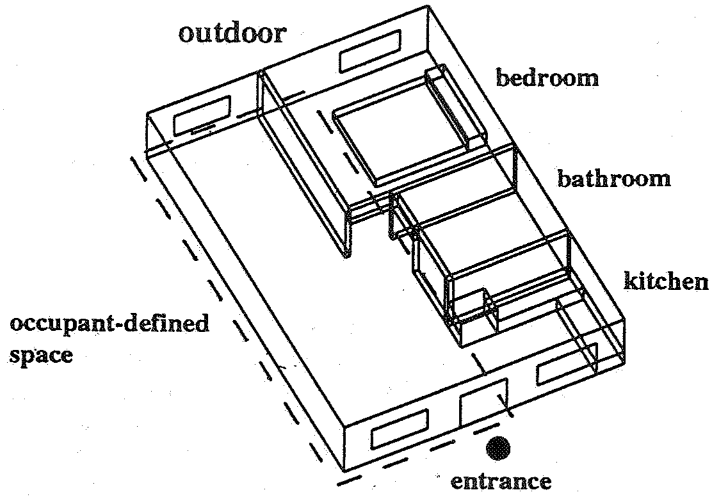

Fig. 1 Apartment unit.

Table 1 Simulation cases.

type	A			B			C		
case/window type	A-1	A-2	A-3	B-1	B-2	B-3	C-1	C-2	C-3
gap[1]	-	-	-	yes	yes	yes	yes	yes	yes
# of wall units	0			1			3		
ach[2]	5.								
inlet velocity (m/s)	0.2789								
inlet area (m^2)	0.36								
outlet area (m^2)	0.72								

[1]gap beneath wall units; [2]number of air changes per hour based on the volume of occupant-defined space.

Table 2 Dimensions and locations of windows and wall units.

DIMENSION (m)	X	Y	Z	LOCATION[1] (m)	X	Y	Z
space	8.74	3.42	3.00	type 1 inlet (A-1, B-1, C-1)	0.00	1.20	0.10
type 1 inlet (A-1, B-1, C-1)	0.00	1.20	0.30	type 2 inlet (A-2, B-2, C-2)	0.00	1.80	0.10
type 2 inlet (A-2, B-2, C-2)	0.00	0.60	0.60	type 3 inlet (A-3, B-3, C-3)	0.00	1.80	0.90
type 3 inlet (A-3, B-3, C-3)	0.00	0.60	0.60	outlet	8.74	0.00	2.10
outlet	0.00	2.40	0.30	wall unit #1	3.92	0.00	0.10
wall unit #1	0.40	1.20	1.40	wall unit #2	6.94	0.00	0.10
wall unit #2	0.40	1.20	2.00	wall unit #3	6.94	1.20	0.10
wall unit #3	0.40	1.20	1.10	block	3.92	2.40	0.00
block	3.92	1.02	3.00	heat / pollutant source #1	1.60	0.60	0.50
heat / pollutant source	0.20	0.20	0.30	heat / pollutant source #2	5.32	0.60	0.50
				heat / pollutant source #3	7.94	0.60	0.50

[1]measured from the origin to the lower left corner of each object, viewed from the direction of outlet.

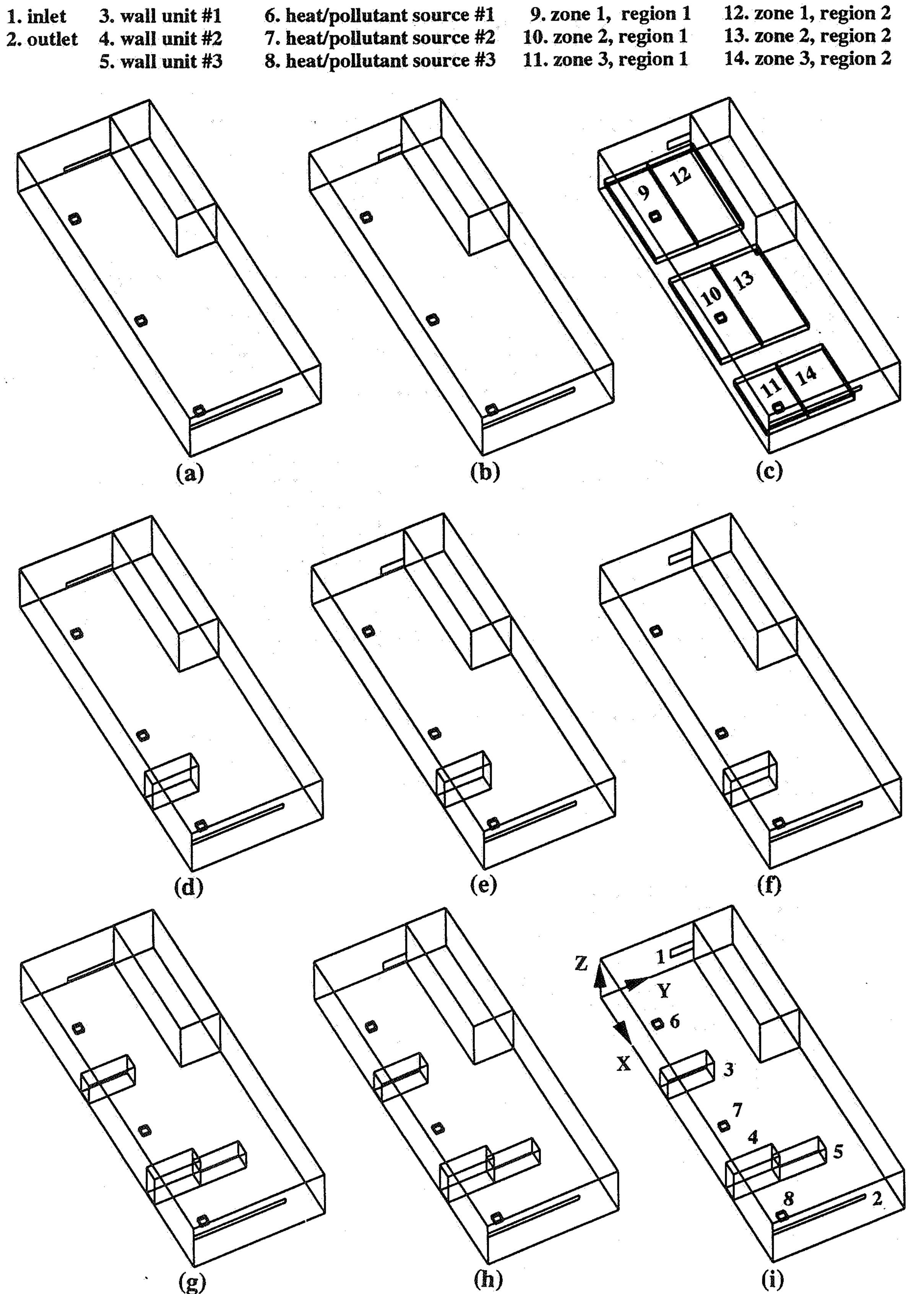

Fig. 2 Nine cases, (a) A-1, (b) A-2, (c) A-3, (d) B-1, (e) B-2, (f) B-3, (g) C-1, (h) C-2, and (i) C-3.

Table 3 Performance of case A-1, B-1 and C-1.

type/case	A-1		B-1		C-1	
T_{out} [1] (°C)	30.08		30.07		30.03	
C_{out} [2] (ppm)	119.3		119.4		117.8	
thermal comfort in zone 1 (PMV)	1.36_1	1.33_2	1.38_1	1.34_2	1.35_1	1.33_2
thermal comfort in zone 2 (PMV)	1.32_1	1.28_2	1.32_1	1.29_2	1.31_1	1.28_2
thermal comfort in zone 3 (PMV)	1.29_1	1.24_2	1.31_1	1.27_2	1.32_1	1.27_2
draft risk in zone 1 (%)	0.73_1	0.60_2	0.24_1	0.51_2	0.07_1	0.25_2
draft risk in zone 2 (%)	0.48_1	1.65_2	0.06_1	0.69_2	0.17_1	0.06_2
draft risk in zone 3 (%)	0.11_1	0.41_2	0.17_1	0.00_2	0.13_1	0.01_2
CO_2 concentration in zone 1 (ppm)	14.79_1	6.42_2	14.96_1	8.12_2	13.92_1	7.94_2
CO_2 concentration in zone 2 (ppm)	10.36_1	4.40_2	16.24_1	7.51_2	13.94_1	7.94_2
CO_2 concentration in zone 3 (ppm)	10.28_1	3.14_2	12.70_1	4.85_2	12.32_1	4.59_2

$_1$lower left region in each zone; $_2$lower right region in each zone; [1]T_{out}: average temperature at the outlet; [2]C_{out}: average CO_2 concentration at the outlet.

Table 4 Performance of case A-2, B-2 and C-2.

type/case	A-2		B-2		C-2	
T_{out} [1] (°C)	30.05		30.04		30.03	
C_{out} [2] (ppm)	120.6		119.5		121.3	
thermal comfort in zone 1 (PMV)	1.35_1	1.29_2	1.36_1	1.30_2	1.31_1	1.25_2
thermal comfort in zone 2 (PMV)	1.33_1	1.28_2	1.30_1	1.28_2	1.27_1	1.24_2
thermal comfort in zone 3 (PMV)	1.30_1	1.25_2	1.33_1	1.28_2	1.32_1	1.27_2
draft risk in zone 1 (%)	0.91_1	1.63_2	0.63_1	1.66_2	0.09_1	1.19_2
draft risk in zone 2 (%)	0.81_1	1.84_2	0.40_1	1.11_2	0.41_1	0.21_2
draft risk in zone 3 (%)	0.42_1	0.70_2	0.16_1	0.00_2	0.11_1	0.00_2
CO_2 concentration in zone 1 (ppm)	24.53_1	17.89_2	22.64_1	17.25_2	16.15_1	8.04_2
CO_2 concentration in zone 2 (ppm)	18.73_1	12.25_2	21.76_1	11.94_2	11.31_1	6.28_2
CO_2 concentration in zone 3 (ppm)	18.26_1	9.84_2	16.62_1	9.68_2	11.69_1	4.60_2

$_1$lower left region in each zone; $_2$lower right region in each zone; [1]T_{out}: average temperature at the outlet; [2]C_{out}: average CO_2 concentration at the outlet.

Table 5 Performance of case A-3, B-3 and C-3.

type/case	A-3		B-3		C-3	
T_{out} [1] (°C)	29.88		29.86		29.89	
C_{out} [2] (ppm)	113.2		115.1		113.5	
thermal comfort in zone 1 (PMV)	1.31_1	1.16_2	1.32_1	1.16_2	1.20_1	1.09_2
thermal comfort in zone 2 (PMV)	1.33_1	1.27_2	1.27_1	1.27_2	1.25_1	1.22_2
thermal comfort in zone 3 (PMV)	1.31_1	1.26_2	1.36_1	1.30_2	1.35_1	1.28_2
draft risk in zone 1 (%)	0.34_1	2.62_2	0.27_1	2.71_2	0.52_1	2.78_2
draft risk in zone 2 (%)	0.64_1	1.65_2	0.93_1	1.08_2	0.52_1	0.55_2
draft risk in zone 3 (%)	0.69_1	0.12_2	0.14_1	0.00_2	0.17_1	0.03_2
CO_2 concentration in zone 1 (ppm)	33.99_1	27.68_2	38.29_1	32.39_2	21.56_1	19.17_2
CO_2 concentration in zone 2 (ppm)	39.19_1	29.12_2	40.40_1	33.39_2	25.02_1	21.19_2
CO_2 concentration in zone 3 (ppm)	39.91_1	29.74_2	36.31_1	31.39_2	26.19_1	20.46_2

$_1$lower left region in each zone; $_2$lower right region in each zone; [1]T_{out}: average temperature at the outlet; [2]C_{out}: average CO_2 concentration at the outlet.