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A multi-objective study on the operation of task/ambient air conditioning systems in subtropics

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Abstract

Task/ambient air conditioning (TAC) system is reported to be an energy efficient technology with available methods to control thermal comfortable level for sleeping environments. However, for real application the varied envelope thermal load should be considered. To determine the optimum operation under different envelope thermal load, an optimization of the TAC system operation was carried out in this study. A multi-objective optimization approach named TOPSIS method was used to evaluate the integrated performance of the TAC system. Finally, the ranking of the selected study cases was obtained and the optimum operation was achieved.

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Keywords: TAC system, optimum operation, energy consumption, thermal comfort, envelope thermal load, TOPSIS

1. Introduction

There has been an increasing interest in using task/ambient air conditioning (TAC) systems, due to their better performance in energy saving and maintaining thermal comfortable environment [1, 2]. A TAC system was defined

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as a space conditioning system that permits thermal environment in a small and local area to be individually controlled [3]. In recent years, there have been a lot of studies conducted on TAC systems [4, 5, 6].

Nomenclature

C_p	Specific heat at constant pressure (ºC)
Q_c	Energy consumption (W)
Q_s	Supply air flow rate (l/s)
t_e	envelope exterior wall temperature (ºC)
t_r	Return air temperature (ºC)
t_s	Supply air temperature (ºC)
R	Radiative heat loss (W/m^2)
E_{sk}	Evaporative heat loss from skin (W/m^2)
C_{res}	Sensible heat loss due to respiration (W/m^2)
E_{res}	Latent heat loss due to respiration (W/m^2)

Parts of these studies focused on the operating performance of the TAC system. The operating parameters of the systems were controlled to realize a suitable performance. For a floor-based TAC system, Bauman et al. [3] recommended that local supply temperatures be maintained at above 17 ºC to avoid uncomfortable cold draft for the occupants nearby. Gong et al. [7, 8] suggested that when a task\ambient supply outlet was 15 cm away from an occupant, a supply velocity of 0.3 to 0.45 m/s would be suitable at a supply air temperature of 21 ºC, while a supply air velocity of 0.3 to 0.9 m/s was better at a supply temperature of 23.5 ºC. Niu et al. [9] investigated a chair-based personalized ventilation system, and suggested that the air flow rate can be limited below 1.2 l/s to prevent the draft risk. In this study, the air temperature was set at 15, 18, and 22 ºC. It's found that suitable air flowrate can maintain a thermal comfortable level. Stefano et al. [10] studied a personalized ventilation system in an office in hot and humid climates. The results show that, compared to the total volume ventilation, the highest energy saving performance (51%) was achieved at supply air temperature of 24 ºC, supply air flow rate of 2.5 l/s and room set temperature of 28 ºC. Faculdade et al. [11] evaluated a desk based personalized ventilation system in a classroom. The air temperature was set at 28 ºC, and air flowrate was set at 60.3 m^3/h at upper supplier and 45.6 m^3/h at lower supplier. Mao et al. [12] also carried out research on bedroom mounted TAC system. The supply air temperatures were set at 19 and 21 ºC, and supply air flowrate at 50, 80 and 100 l/s. It's found that the energy utilization coefficient of the TAC system was about 1.9 which was much higher than that of a traditional full volume air conditioning system. The supply vane angle of the air conditioning system was investigated in a previous optimization study [13]. The optimal angle to achieve the best performance was obtained using TOPSIS method. Moreover, the previous studies on thermal comfort in sleeping environment [14, 15] provide a solid fundamental for the further study on operation of TAC to maintain thermal comfort level during night.

During nighttime, the outdoor air temperature or cooling load varies obviously [16, 17, 18, 19]. Due to the heat transfer through the envelope, the variation of outdoor air temperature results to the change of indoor air temperature [20].Therefore, corresponding to the changing thermal load, how to maintain the TAC system at a suitable energy saving status is a crucial issue. In this paper, firstly, a multi-objective optimization method was introduced. Thereafter, the thermal comfort level and energy consumption of a TAC system was evaluated using TOPSIS method.

2. Numerical modeling

Computational fluid dynamics (CFD), as the most sophisticated airflow modelling method, can simultaneously predict airflow and heat transfer in buildings [21, 22, 23, 24, 25, 26, 27]. The information provided by CFD can be used to evaluate the thermal environment and energy saving performance of air conditioning systems in buildings. Therefore, a commercial CFD code Fluent was used in this study to investigate a TAC system equipped in a bedroom [28, 29]. The bedroom was constructed in an environmental chamber [12, 30, 31, 32, 33, 34] which was divided into two adjacent rooms for simulating different thermal environments: Room A and Room B, as shown in Figs. 1. Room B was further separated into a larger space to simulate a bedroom, and a smaller space to simulate the outdoor environment. In Room A, the direct expansion (DX) A/C plant and sensible heat and moisture load generating units (LGUs) are responsible for maintaining the air temperature and humidity inside the chamber at normal A/C operations [35, 36, 37, 38, 39].

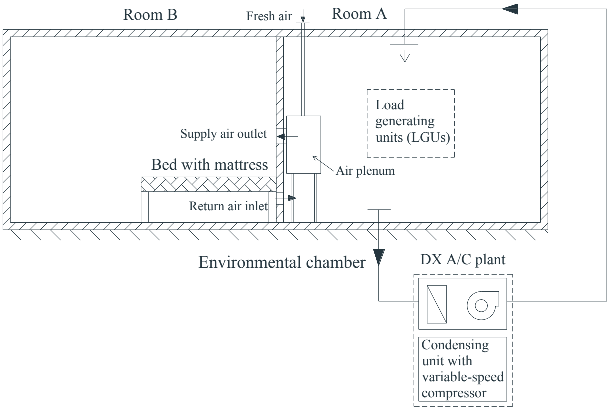
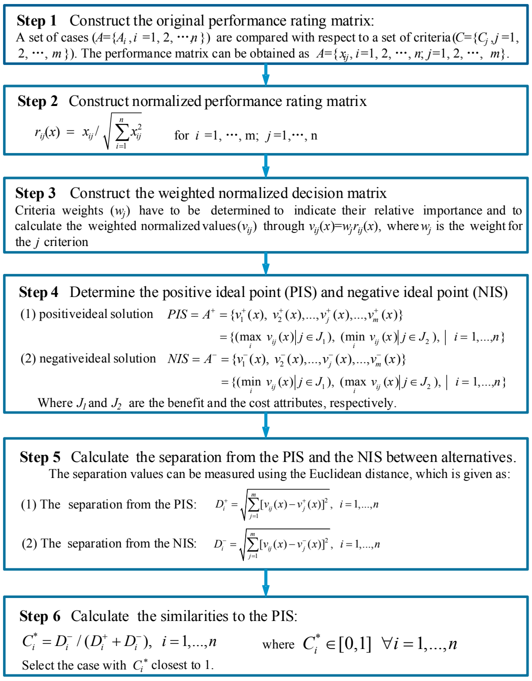


Fig. 1 The environmental chamber

3. Multi-objective optimization

3.1. TOPSIS method

TOPSIS is a simple ranking method which attempts to choose alternatives that simultaneously have the shortest distance from the positive ideal solution (PIS) and the farthest distance from the negative ideal solution (NIS) [40, 41, 42]. The schematic of this method is shown in Fig 2. The PIS maximizes the benefit indexes and minimizes the cost indexes, whereas the NIS maximizes the cost indexes and minimizes the benefit indexes. TOPSIS gives a method to calculate the distance from one alternative to PIS and NIS, which makes full use of attribute information, and provides a cardinal ranking of alternatives [43].



Step 1 Construct the original performance rating matrix:
A set of cases ($A=\{A_i, i=1, 2, \cdots n\}$) are compared with respect to a set of criteria ($C=\{C_j, j=1, 2, \cdots, m\}$). The performance matrix can be obtained as $A=\{x_{ij}, i=1, 2, \cdots, n; j=1, 2, \cdots, m\}$.

Step 2 Construct normalized performance rating matrix

$$r_{ij}(x) = x_{ij} / \sqrt{\sum_{i=1}^{n} x_{ij}^2} \qquad \text{for } i=1, \cdots, \text{m}; \ j=1, \cdots, \text{n}$$

Step 3 Construct the weighted normalized decision matrix
Criteria weights (w_j) have to be determined to indicate their relative importance and to calculate the weighted normalized values (v_{ij}) through $v_{ij}(x)=w_j r_{ij}(x)$, where w_j is the weight for the j criterion

Step 4 Determine the positive ideal point (PIS) and negative ideal point (NIS)

(1) positiveideal solution $PIS = A^+ = \{v_1^+(x), v_2^+(x), \ldots, v_j^+(x), \ldots, v_m^+(x)\}$

$$= \{(\max_i v_{ij}(x) | j \in J_1), (\min_i v_{ij}(x) | j \in J_2), | \ i = 1, \ldots, n\}$$

(2) negativeideal solution $NIS = A^- = \{v_1^-(x), v_2^-(x), \ldots, v_j^-(x), \ldots, v_m^-(x)\}$

$$= \{(\min_i v_{ij}(x) | j \in J_1), (\max_i v_{ij}(x) | j \in J_2), | \ i = 1, \ldots, n\}$$

Where J_1 and J_2 are the benefit and the cost attributes, respectively.

Step 5 Calculate the separation from the PIS and the NIS between alternatives.
The separation values can be measured using the Euclidean distance, which is given as:

(1) The separation from the PIS: $D_i^+ = \sqrt{\sum_{j=1}^{m} [v_{ij}(x) - v_j^+(x)]^2}, \ i = 1, \ldots, n$

(2) The separation from the NIS: $D_i^- = \sqrt{\sum_{j=1}^{m} [v_{ij}(x) - v_j^-(x)]^2}, \ i = 1, \ldots, n$

Step 6 Calculate the similarities to the PIS:

$C_i^* = D_i^- / (D_i^+ + D_i^-), \ i = 1, \ldots, n$ where $C_i^* \in [0,1] \ \forall i = 1, \ldots, n$

Select the case with C_i^* closest to 1.

Fig. 2 Schematic of TOPSIS method

3.2. Weight determination

The weights determination is a critical step when using TOPSIS method. Weights of indexes reflect the relative importance in evaluating process. To utilize the real data and avoid the interruption from human beings, an objective weight determination method named Entropy Method was adopted in this study.

4. Results and analysis

4.1. Original and normalized data

According to the results of the previously reported experimental and numerical study on the TAC system, a supply air temperature between 20 ºC and 26 ºC and a supply air flow rate between 10 l/s and 50 l/s were used. The envelope exterior temperature was selected between 25 ºC and 35 ºC. There are totally 27 cases studied, as shown in Table 1. The thermal comfort level and energy consumption at each case were calculated.

Based on thermal comfort model and considering the heat generation and balance for a sleeping person, Lin and Deng [44] developed an equation to evaluate the PMV index in sleeping environments:

$$PMV = 0.0998\left[40-\left(C+R+E_{sk}+C_{res}+E_{res}\right)\right] \tag{1}$$

In this study, the TAC system was responsible for cooling down the air temperature and dehumidifying the moisture from thermal manikin. Therefore, the energy consumed can be calculated using the following equation.

$$Q_c = \rho Q_s C_p \cdot (t_s - t_r) + \dot{m}\Delta h \tag{2}$$

Where *m* is the moisture generating rate, which was set at 40 g/h according previous studies [45], and Δh is the latent heat of condensation.

The original values of PMV and Qc were calculated using equation (1) and (2), which were normalized following Fig. 2, as shown in Table 1.

Table 1 Study cases and calculated PMV and Q_c values

Case No.	t_s (ºC)	Q_s (l/s)	t_e (ºC)	Original		Normalized	
				PMV	Q_c (W)	PMV	Q_c
T20Q10L25	20	10	25	-0.98	158.79	0.0280	0.0390
T20Q10L35	20	10	35	0.18	374.77	0.0051	0.0921
T20Q50L25	20	50	25	-3.63	106.17	0.1035	0.0261
T20Q50L35	20	50	35	-3.27	203.24	0.0933	0.0499
T26Q10L25	26	10	25	0.48	19.23	0.0137	0.0047
T26Q10L35	26	10	35	2.12	228.19	0.0605	0.0561
T26Q50L25	26	50	25	-0.71	32.49	0.0203	0.0080
T26Q50L35	26	50	35	1.39	228.19	0.0396	0.0561
T20Q10L30	20	10	30	-0.25	260.93	0.0071	0.0641
T20Q50L30	20	50	30	-3.45	149.05	0.0984	0.0366
T26Q10L30	26	10	30	1.23	115.52	0.0351	0.0284
T26Q50L30	26	50	30	0.27	73.42	0.0077	0.0180
T20Q30L25	20	30	25	-2.52	103.05	0.0719	0.0253
T20Q30L30	20	30	30	-2.23	180.63	0.0636	0.0444
T20Q30L35	20	30	35	-1.9	242.22	0.0542	0.0595
T26Q30L25	26	30	25	-0.05	19.23	0.0014	0.0047
T26Q30L30	26	30	30	0.27	73.42	0.0077	0.0180

Table 1 Study cases and calculated PMV and Q_c values (to be continued)

Case No.	t_s (ºC)	Q_s (l/s)	t_e (ºC)	Original		Normalized	
				PMV	Q_c (W)	PMV	Q_c
T26Q30L35	26	30	35	0.29	154.12	0.0083	0.0379
T23Q10L25	23	10	25	-0.08	90.96	0.0023	0.0223
T23Q10L30	23	10	30	0.59	188.03	0.0168	0.0462
T23Q10L35	23	10	35	0.69	302.65	0.0197	0.0743
T23Q30L25	23	30	25	-1.23	78.88	0.0351	0.0194
T23Q30L30	23	30	30	-1.04	137.74	0.0297	0.0338
T23Q30L35	23	30	35	-0.9	199.73	0.0257	0.0491
T23Q50L25	23	50	25	-1.96	69.13	0.0559	0.0170
T23Q50L30	23	50	30	-1.79	116.69	0.0511	0.0287
T23Q50L35	23	50	35	-1.56	164.64	0.0445	0.0404

4.2. Estimation of weights

The weights for PMV and Q_c were calculated and shown in Table 2. According to the entropy theory, the less dispersion the lower weight of the index is. As seen, the weight for PMV was much higher than that for Qc, suggesting that as compared to Q_c, the PMV values would have less variation and was therefore relatively less important. The weights based on data in Table 1 were calculated and shown in Table 2.

Table 2 Weights of the each criterion

Item	Parameter	PMV	*Qc*
1	Ej	0.6559	0.9494
2	Divergence	0.3441	0.05061
3	Weight	0.8718	0.1282

4.3. Optimum operation

Table 3 The weighted normalized decision matrix and results (distance, similarity and ranking)

Case No.	PMV	Q_c	D_i^+	D_i^-	C_i*	Ranking
T20Q10L25	0.0244	0.0050	0.0235	0.0662	0.7378	13
T20Q10L35	0.0045	0.0118	0.0117	0.0858	0.8804	8
T20Q50L25	0.0903	0.0033	0.0891	0.0085	0.0867	27
T20Q50L35	0.0813	0.0064	0.0803	0.0105	0.1152	25
T26Q10L25	0.0119	0.0006	0.0107	0.0791	0.8810	7
T26Q10L35	0.0527	0.0072	0.0519	0.0378	0.4216	22
T26Q50L25	0.0177	0.0010	0.0164	0.0734	0.8172	10
T26Q50L35	0.0346	0.0072	0.0340	0.0559	0.6220	17
T20Q10L30	0.0062	0.0082	0.0091	0.0841	0.9025	6
T20Q50L30	0.0858	0.0047	0.0846	0.0084	0.0903	26
T26Q10L30	0.0306	0.0036	0.0295	0.0602	0.6713	16
T26Q50L30	0.0067	0.0023	0.0057	0.0841	0.9362	3
T20Q30L25	0.0627	0.0032	0.0615	0.0289	0.3198	24
T20Q30L30	0.0554	0.0057	0.0544	0.0353	0.3936	23
T20Q30L35	0.0472	0.0076	0.0465	0.0432	0.4815	20

Table 3 The weighted normalized decision matrix and results (distance, similarity and ranking) (to be continued)

Case No.	PMV	Q_c	D_i^+	D_i^-	C_i*	Ranking
T26Q30L25	**0.0012**	**0.0006**	**0.0000**	**0.0897**	**1.0000**	**1**
T26Q30L30	0.0067	0.0023	0.0057	0.0841	0.9362	4
T26Q30L35	0.0072	0.0049	0.0073	0.0833	0.9192	5
T23Q10L25	0.0020	0.0029	0.0024	0.0887	0.9739	2
T23Q10L30	0.0147	0.0059	0.0144	0.0758	0.8400	9
T23Q10L35	0.0172	0.0095	0.0182	0.0731	0.8003	11
T23Q30L25	0.0306	0.0025	0.0294	0.0604	0.6726	15
T23Q30L30	0.0259	0.0043	0.0249	0.0648	0.7225	14
T23Q30L35	0.0224	0.0063	0.0219	0.0681	0.7568	12
T23Q50L25	0.0487	0.0022	0.0475	0.0426	0.4729	21
T23Q50L30	0.0445	0.0037	0.0434	0.0465	0.5172	19
T23Q50L35	0.0388	0.0052	0.0378	0.0519	0.5784	18

According to steps in Fig. 2, PIS was calculated at (weighted normalized {PMV, Q_c}={0.0012, 0.0006}), and NIS at (weighted normalized { PMV, Q_c }={0.0903, 0.0118}). The separations from the PIS and the NIS were calculated and then the similarities to the ideal solution were obtained, and shown in Table 3. The ranking list was given based on the similarities. It indicates that the case T26Q30L25 was the best angle, with the weighted normalized PMV, Q_c and Ci* at the values of 0.0012, 0.0006, and 0.0897, respectively. From the original values in Table 1, it can be seen that PMV is close to zero and energy consumption is lower at this angle.

5. Conclusions

To find the best operating conditions, TOPSIS method was used to evaluate the thermal comfort and energy consumption of the TAC system. Finally, the case T26Q30L25 was found to be the optimum case. At this case, the PMV value was calculated at -0.05, approximating thermal neutral level, and the energy consumption was 19.23, which also located at a low energy consumption level. Therefore, the TAC at this case can achieve the best performance. Meanwhile, it should be noticed that there is still a case the Q_c of which was as lower as T26Q30L25. However, the thermal environment at this case was slightly warm. Hence, this case can not achieve the best performance. Therefore, this study also indicates that the TOPSIS method can be effectively used for evaluating the combined effects of energy consumption and thermal comfort.

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