3C DUCT DESIGN METHOD

Huan-Ruei Shiu * **Feng-Chu Ou** ** **Sih-Li Chen** **

Department of Mechanical Engineering
National Taiwan University
Taipei, Taiwan 10617, R.O.C.

ABSTRACT

A new 3C duct design method is proposed for designing a high quality, energy-efficiency cost-effective air duct system. It not only considers the demand of volume flow rate, but also takes into consideration a number of issues including system pressure balance, noise, vibration, space limitation and total system cost. This new method comprises three major calculation procedures: initial computer-aided design (CAD), computer-aided simulation (CAS) and correction processes (CP). An example is presented in this study to understand the characteristics of 3C method. It shows that 3C duct design method provides a simple computation procedure for an optimum air duct system. It also shortens the design schedule, prevents human calculation errors, and reduces the dependence on designer experience. In addition to apply in a new duct system design, 3C duct design method is also a powerful design tool for the expansion of an existing duct system.

Keywords : 3C duct design method, Semiconductor factory, Exhaust system, HVAC.

1. INTRODUCTION

Duct design is important for commercial, industrial, and residential air duct systems. An optimum air duct system transports the required amount of conditioned, recirculated, or exhausted air to the specific space and meets the following requirements: (1) an optimum duct system layout within the allocated space, (2) a satisfactory system pressure balance, (3) space noise level lower than the allowable limits, and (4) optimum energy cost and initial cost. Deficiencies in duct design can result in systems that operate incorrectly and increase the initial or running cost.

Most conventional Heating, Ventilating, and Air-Conditioning (HVAC) duct design methods consist of equal velocity, equal friction, balanced capacity (pressure), and static regain. The equal velocity method or the equal friction method may be simple, but they fail to achieve pressure balance. Thus, the system designed does not meet the actual operations. On-site ventilation adjustment after project completion becomes necessary. In some cases, large fans must be installed to make up for poor designs, which add to extra cost. Shieh [1] improved the static regain method to simplify the calculation procedures and ensure the advantage of system pressure balance. However it does not contain the cost concept, like other conventional design method, and thus cannot meet the optimization requirement.

T-method proposed by Tsal, *et al.*, [2~4] is the most comprehensive and powerful tool applied in duct design. It uses iteration computation and cost optimization theory, which enable the designed system to have the lowest life cycle cost and all paths to have the same pressure loss. There is no need to waste extra time or money to attain system pressure balance. However, T-method offers poor control of flow velocity or duct diameter. In cases of relatively inexpensive initial cost, the flow velocity may be too high. In contrast, for cases of relatively inexpensive energy cost, the duct size may be too big. Nevertheless, in actual duct design, considerations of the factors of space and noise often require the limit on the duct diameter or flow velocity during certain sections. When there are too many limitations, it is difficult to obtain the satisfactory optimal solution from T-method. Thus, a new 3C design method, which is suitable for the duct system design, is proposed in this paper.

2. 3C DUCT DESIGN METHOD

For a complete duct design case, one should provide the information on the given design conditions and limitations. Given design conditions and limitations regarding the duct system include (1) basic information: such as duct system layout, liquid physical property and duct materials; (2) system requirements: such as volume flow rate, length and cross section shape; (3) duct

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* Graduate student ** Professor

information: such as the loss coefficient of various accessories and equipments [5,6]; (4) safety concerns: such as the minimum velocity for safety [7] or the maximum velocity to prevent vibrations and noise [8]; (5) cost concern: such as total duct surface area or the volume flow rate and performance of the fan.

The significance of 3C duct design method is in correcting system design values based on operation results in order to achieve the goal of precise design, i.e., the introduction of feedback design. The principle of 3C duct design method is very similar to the feedback control in dynamic system. According to the principle of feedback control, system devices utilize error signals to adjust the control variable. The same concept is introduced to duct design as the essence of 3C design method. The feedback concept in 3C duct design method is shown in Fig. 1, which includes three major procedures:

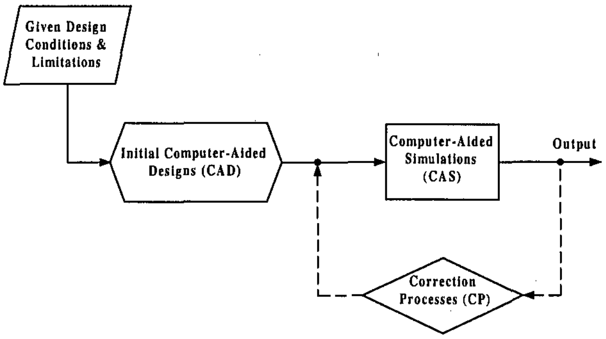

Fig. 1 Design concept of 3C duct design method

2.1 Initial Computer-Aided Design (CAD)

The objective of this procedure is to select a conventional design method based on system characteristics and requirement. The initial design methods would be velocity method, equal friction method, static regain method or T-method. In this paper equal friction method is adopted as a tool for initial design. The strengths of this method include: (1) simple calculation procedures; (2) easy control of velocity within the duct. The weaknesses include: (1) it is not suitable for a system containing a number of ducts at different lengths, and difficulty in maintaining system pressure equilibrium; (2) it is necessary to determine the accessory loss coefficient by estimation in advance, which lowers the precision; (3) the method lacks cost considerations.

2.2 Computer-Aided Simulation (CAS)

In reality, the total pressure drop is equal on all paths. For a system originally designed with unbalanced pressure, once in operation, the system will automatically adjust the velocity and volume flow rate in all duct sections to achieve equal total pressure loss on all paths. In this case, the velocity and volume flow rate will not meet the original design requirements. System simulation is performed after the initial design or the correction process is completed in order to verify the actual operating performance of the system. System simulation also determines the flow in each duct section of an existed system with a known operating fan performance curve. The theory proposed by Tsal, *et al.* [4] related to system simulation methods is adopted in this paper. It includes the major procedures of system condensing, fan operating point and system expansion.

First, the total friction loss from the Darcy-Weisbach equation for round duct is:

$$\Delta P_t = \left(\frac{fL}{D} + \sum C\right) \cdot \frac{8\rho}{\pi^2} \cdot Q^2 D^{-4} \qquad (1)$$

If μ is defined as

$$\mu = \left(\frac{fL}{D} + \sum C\right) \cdot D \qquad (2)$$

the volume flow rate can be identified in terms of diameter and pressure loss by coefficient μ. Thus,

$$Q = \frac{\pi}{\sqrt{8}} \cdot \left(\frac{D^5}{\mu\rho}\right)^{0.5} \cdot \sqrt{\Delta P} \qquad (3)$$

By introducing the duct section characteristic K_S

$$K_S = \frac{\pi}{\sqrt{8}} \left(\frac{D^5}{\mu\rho}\right)^{0.5} \qquad (4)$$

Then, the flow rate at a duct section becomes

$$Q = K_S \sqrt{\Delta P} \qquad (5)$$

Physically, the sectional coefficient K_S can be called as duct conductance.

System Condensing

This procedure condenses a branched tee into a single imaginary duct section with identical hydraulic characteristics. Two or more converging or diverging sections and the common section at a junction can be replaced by one condensed section. From junction to junction in the direction to the root section, the entire system, including supply and return subsystems, can be condensed into one imaginary section, i.e., a single resistance. System curve can be determined.

(a) Series: The system in Fig. 2 contains two duct sections connected in series. To introduce an imaginary duct section (1-2) this section must satisfy the following conditions:

flow rate: $Q_{1\text{-}2} = Q_1 = Q_2$ (5a)

pressure loss: $\Delta P_{1\text{-}2} = \Delta P_1 + \Delta P_2$ (5b)

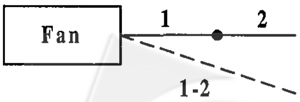

Fig. 2 Condensing two sections connected in series

Substituting Eq. (4) into Eq. (5b) obtains

$$\frac{Q_{1\text{-}2}^2}{Ks_{1\text{-}2}^2} = \frac{Q_1^2}{Ks_1^2} + \frac{Q_2^2}{Ks_2^2} \qquad (5c)$$

Substituting Eq. (5a) into Eq. (5c), the imaginary duct section characteristics can be obtained as

$$K_{S_{1\text{-}2}} = (K_{S_1}^{-2} + K_{S_2}^{-2})^{-0.5} \qquad (6)$$

(b) Parallel: Two sections, 1 and 2, in parallel can be condensed into an imaginary section (1-2), as shown in Fig. 3. The condensed section must satisfy the following conditions:

$$\text{flowrate:} \quad Q_{1\text{-}2} = Q_1 + Q_2 \qquad (7a)$$

$$\text{pressure loss:} \quad \Delta P_{1\text{-}2} = \Delta P_1 = \Delta P_2 \qquad (7b)$$

From Eq. (4) and Eq. (7), K_S of condensed duct section (1-2) is

$$K_{S_{1\text{-}2}} = K_{S_1} + K_{S_2} \qquad (8)$$

This equation is derived when the degree of a node is two. Similarly, if the degree of a node is more than 2 (i.e., the conductance coefficient is K_{S1}, K_{S2}, $\cdots$, K_{Sn}), this equation becomes

$$K_{S_{1\text{-}n}} = \sum_{i=1}^{n} K_{S_i} \qquad (9)$$

(c) Condensing a Tee: Consider the tee shown in Fig. 4 which contains one node, two sections 2 and 3 in parallel, and one section 1 in series. First, condense the parallel sections 2 and 3 to form section 2-3, and then condense series sections 2-3 and 1 into section 1-3 to obtain Eq. (10).

$$K_{S_{1\text{-}3}} = [K_{S_1}^{-2} + (K_{S_2} + K_{S_3})^{-2}]^{-0.5} \qquad (10)$$

Fan Operating Point

This step determines system flow rate and total pressure by locating the intersection of the system curve and fan performance curve.

When the system condensing is completed, the duct system arrives at only one fan and one imaginary duct section. Therefore, from Eq. (4) we obtain Eq. (11), where K_S is replaced by the coefficient of conductance for the system, $K_{S,sys}$. The system curve becomes

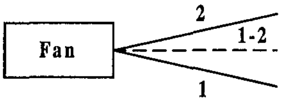

Fig. 3 Condensing two sections connected in parallel

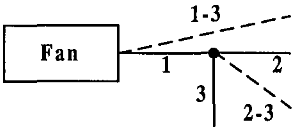

Fig. 4 Condensing three sections connected in tee

$$Q_{sys} = K_{S,sys}\sqrt{\Delta P_{sys}} \qquad (11)$$

When the system is operated, the fan actual operating point is at the intersection of system curve and fan performance curve. That is $Q_{sys} = Q_{fan}$ and $P_{sys} = P_{fan}$.

System Expansion

The expansion procedure distributes the fan flow rate Q_{fan} throughout the system sections. Knowing system flow and pressure, the previously condensed imaginary duct section is expanded into the original system with flow distributed in accordance with the ratio of pressure losses calculated in the system condensing step. The expansion procedure starts at the root section and continues in the direction of the terminals. During the design process, system expansion is conducted section by section from upstream to downstream.

2.3 Correction Processes (CP)

The objectives of correction processes are to reduce the error between the actual operation and the design results in order to follow the design requirements and limitation. The correction process is proceeded by correction criterion and correction sequence.

Correction Criterion

The most important parameters in duct system design are the accuracy of volume flow rate at various duct sections and reasonable ventilation velocity in the duct. Correction criterion is to provide designers with a basis for design correction. The correction criterion of 3C design method is developed on the basis of the results of computer simulation. The simulation model utilizes an existing system for testing and imposes a variety of possible system corrections. The correction criterion are summarized for designer reference, as listed in Table 1. The arrow indicates the increase or decrease of the quantity. For example, the flow rate (↑) represents the flow rate increases. As the flow rate or the velocity in the duct system is too large, the damper angle should be adjusted to increase or fan speed should be adjusted to decrease. Then the flow rate or the velocity will tend to be decreased. If the flow rate is too large or the velocity is too small, the duct size should be adjusted to decrease.

Table 1 Adjustment principles

Parameters	Adjustment Methods	Results
Flow Rate (L)	Damper Angle (↑) Fan Speed (↓)	Flow Rate (↓)
Velocity (L)		Velocity (↓)
Flow Rate (L)	Duct Sizes (↓)	Flow Rate (↓)
Velocity (S)		Velocity (↑)
Flow Rate (S)	Duct Sizes (↑)	Flow Rate (↑)
Velocity (L)		Velocity (↓)
Flow Rate (S)	Damper Angle (↓) Fan Speed (↑)	Flow Rate (↑)
Velocity (S)		Velocity (↑)

[Note]: (L) represents the quantity is too large and (S) indicates the quantity is too small.

Correction Sequence

The concept of level deposition is proposed in the 3C method in order to proceed the correction process. That is, each of the branch duct or joint duct in the entire system is given by a proper corrected level based on the relative position of the branch duct or joint duct to the upstream fan. As shown in Fig. 5, eight corrected levels are decomposed in the duct layout on the basis of branch locations. The corrected level 1 begins at branch 1 and passes by two joint ducts 2 and 39. Corrected level 2 includes two branches and ducts 3, 8, 42 and 43. Corrected levels 3 to 8 are demonstrated in Table 2. During the correction process, correction is conducted level by level.

A series of correction principles are conducted as following: (1) It is necessary to ensure that there is sufficient volume flow rate in the upstream level before solving the issue of volume flow rate distribution in downstream level. (2) Adjustment of volume flow rate distribution in downstream level often results in an increase of local resistance. Thus, the volume flow rate in upstream level must be greater than the volume flow rate at the design point to prevent instances of insufficient volume flow rate due to the increase in resistance. (3) The correction of target duct section design has a very limited impact on the upstream duct, but a tremendous impact on the downstream duct and parallel duct section. (4) Volume flow rate adjustment at the target duct section can be achieved through the correction of the upstream duct section, parallel duct section, target duct section itself and system fan. (5) The impact of volume flow rate adjustment at the target duct section must be considered to prevent the velocity from becoming too high or too low.

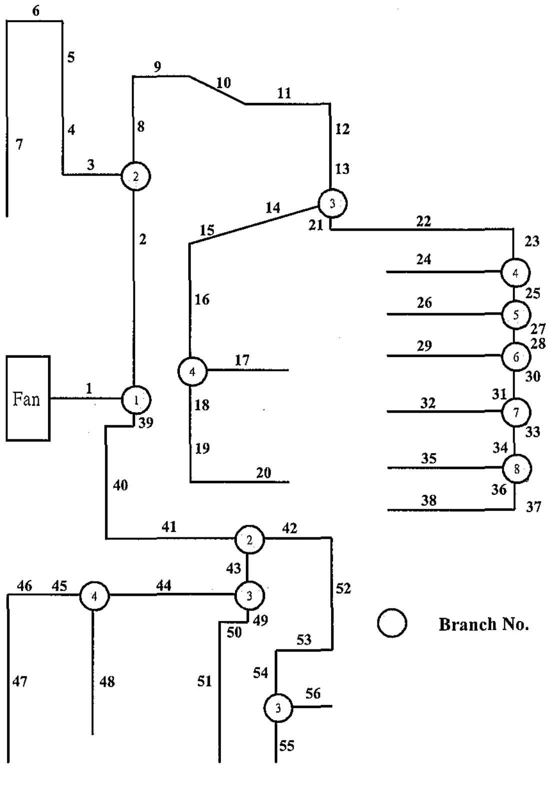

Fig. 5 Duct layout of an alkali exhaust gas system in a semiconductor factory

Table 2 Corrected level classification

Corrected Level	1	2	3	4	5	6	7	8
Duct Section	2 39	3 8 42 43	14 21 44 49 55 56	17 18 45 48 24 25	26 27	29 30	32 33	35 36
Branch No.	1	2	3	3	1	1	1	1

3. EXAMPLE ILLUSTRATION

A real case of alkali gas exhaust system in a semiconductor factory is designed and analyzed though the 3C method, as shown in Fig. 5. Codes are given to different duct sections according to their flow rate, duct diameter and cross section shape. There are a total of 56 duct sections and 14 paths. Both exhaust flow rates and duct section lengths are listed in Table 3. The most important parameters are the designation of safe ventilation velocity and the total volume flow rate, as listed in Table 4. The type of gas emission, humidity, vibration and noise determines the upper and lower limits of safe velocity.

Table 3 Duct sections and flow rate requirements

Duct Section	Flow Rate (m^3/sec)	Length (m)	Duct Section	Flow Rate (m^3/sec)	Length (m)
1	10.620	1.000	29	1.720	21.400
2	8.280	38.000	30	3.050	1.000
3	0.370	3.800	31	3.050	13.400
4	0.370	3.000	32	1.720	21.400
5	0.370	1.500	33	1.330	1.000
6	0.370	9.600	34	1.330	6.000
7	0.370	12.600	35	0.720	18.000
8	7.910	0.500	36	0.610	1.000
9	7.910	2.500	37	0.610	14.400
10	7.910	4.500	38	0.610	22.400
11	7.910	10.500	39	2.340	1.000
12	7.910	14.700	40	2.340	3.200
13	7.910	4.000	41	2.340	2.000
14	2.110	0.500	42	0.820	2.000
15	2.110	6.400	43	1.520	15.000
16	2.110	20.400	44	1.170	3.000
17	1.060	23.000	45	0.700	1.000
18	1.050	2.000	46	0.700	7.000
19	1.050	47.600	47	0.700	12.000
20	1.050	20.200	48	0.470	12.000
21	5.800	0.500	49	0.330	17.500
22	5.800	57.000	50	0.330	8.600
23	5.800	6.000	51	0.330	10.400
24	0.530	22.000	52	0.820	21.500
25	5.270	16.000	53	0.820	15.000
26	0.500	22.000	54	0.820	24.000
27	4.770	1.000	55	0.560	5.000
28	4.770	5.400	56	0.260	10.200

Table 4 Duct system design data

Constrain Conditions	Parameter Values
Safety Velocity (min.)	5m/sec
Safety Velocity (max.)	15m/sec
Friction Loss	1.929Pa/m
Total Volume Flow Rate	$10.70m^3$/sec

Equal friction method is adopted as the initial design on the base of the given conditions. The total pressure losses of all paths are already known to serve as the basis for the selection of fan. The results are shown in Table 5. Path No. 9 has the largest total pressure drop of all, which is the "critical path" in the duct design. It is obvious that there is a considerable discrepancy in the total pressure drop on different paths. In other words, there is a sizable error in the volume flow rate between various duct sections and design points during system operation. Table 6 indicates the design flow rates and simulated flow rates at each section. It shows that in addition to a large discrepancy in volume flow rate, the velocities in duct sections 35 and 38 are obviously too low. Thus, it is necessary to adjust the initial design results and to activate the correction processes.

Table 7 shows the flow rate of design requirements and the results of flow rate from simulation and correction process at each corrected level. At corrected level 1, the simulated volume flow rate in section 2 is $7.961m^3$/s, which is lower than the design values ($8.280m^3$/s). The designed and simulated volume flow rate ratios in sections 2 and 39 are 0.282 and 0.431. Flow rate ratio is defined as the designed flow rate in duct section 2 divided by that in duct section 39. Since the flow rate in duct section 2 is $8.28m^3$/s and in section 39 is $2.34m^3$/s, the flow rate ratio can be written as $8.28/2.34 = 1/x$, $x = 0.282$. For the case of computer-aided simulations, the flow rate ratio in corrected level 1 is the flow rate in duct section 2 divided by that in duct section 39. The flow rate in duct section 2 is $7.961m^3$/s and in section 39 is $3.439m^3$/s. Then the flow rate ratio is 0.431. Table 7 indicates an excessive volume flow rate in section 39. According to the principles of volume flow-rate adjustment in Table 1, correction methods such as reducing the duct diameter, adding accessories and adjusting the damper angle can all be adopted. As shown in Table 8, the correction methods adopted in corrected level 1 include the following: (a) Enlarge the duct diameter of section 2 from 0.873m to 1.0m; (b) Enlarge the duct diameter of section 39 from 0.539m to 0.54m; (c) Add a damper to section 39 and adjust it to an angle of 29°. The results of corrected level 1 are system curve $P = 4.067Q^2$, fan total pressure 489.870Pa, and volume flow rate $10.980m^3$/s. The other corrected levels and correction methods are followed in similar ways. The results are also shown in Table 7 and 8. The 3C duct design of the entire exhaust system is completed after performing all corrected levels. The system curve is $P = 3.780Q^2$. The fan total pressure becomes 473.760Pa and fan volume flow rate is $11.190m^3$/s. The layout of the system is shown in Fig. 6.

Table 5 Initial computer-aided design results at each path

Path No.	Pressure Loss (Pa)	Path
1	134.066	Fan-1-2-3-4-5-6-7
2	243.054	Fan-1-2-8-9-10-11-12-13-14-15-16-17
3	333.331	Fan-1-2-8-9-10-11-12-13-14-15-16-18-19-20
4	310.955	Fan-1-2-8-9-10-11-12-13-21-22-23-24
5	341.819	Fan-1-2-8-9-10-11-12-13-21-22-23-25-26
6	353.007	Fan-1-2-8-9-10-11-12-13-21-22-23-25-27-28-29
7	380.785	Fan-1-2-8-9-10-11-12-13-21-22-23-25-27-28-30-31-32
8	387.729	Fan-1-2-8-9-10-11-12-13-21-22-23-25-27-28-30-31-33-34-35
9	425.923	Fan-1-2-8-9-10-11-12-13-21-22-23-25-27-28-30-31-33-34-36-37-38
10	87.191	Fan-1-39-40-41-43-44-45-46-47
11	71.759	Fan-1-39-40-41-43-44-48
12	113.232	Fan-1-39-40-41-43-49-50-51
13	144.096	Fan-1-39-40-41-42-52-53-54-55
14	154.127	Fan-1-39-40-41-42-52-53-54-56

Table 6 Initial computer-aided simulation results (level 0)

Duct Section	Design Flow Rate (m^3/sec)	Simulation Flow Rate (m^3/sec)	Simulation Velocity (m/sec)	Diameter (m)
7	0.370	0.832	14.645	0.269
17	1.060	1.604	12.830	0.399
20	1.050	0.909	7.345	0.397
24	0.530	0.692	9.354	0.307
26	0.500	0.534	7.503	0.301
29	1.720	1.512	8.354	0.480
32	1.720	1.161	6.414	0.480
35	0.720	0.455	4.872	0.345
38	0.610	0.262	3.175	0.324
47	0.700	1.054	11.611	0.340
48	0.470	0.959	14.120	0.294
51	0.330	0.448	8.632	0.257
55	0.560	0.742	9.584	0.314
56	0.260	0.236	5.438	0.235

Table 7 Results of design, simulation and correction from corrected level 1 to 8

Corrected Level	Duct Section	Design Requirements		Computer-Aided Simulations			Correction Processes		
		Flow Rate (m^3/sec)	Flow Rate Ratio	Flow Rate (m^3/sec)	Flow Rate Ratio	Velocity (m/sec)	Flow Rate (m^3/sec)	Flow Rate Ratio	Velocity (m/sec)
1	2	8.280	1	7.961	1	13.301	8.562	1	10.901
	39	2.340	0.282	3.439	0.431	15.070	2.418	0.282	10.558
2	3	0.370	0.047	0.895	0.116	15.751	0.377	0.045	12.008
	8	7.910	1	7.667	1	13.260	8.356	1	10.639
	42	0.820	0.539	0.686	0.396	6.669	0.851	0.540	6.448
	43	1.520	1	1.732	1	10.511	1.576	1	9.907
3	14	2.110	0.364	2.947	0.545	13.930	2.319	0.377	14.910
	21	5.800	1	5.409	1	11.860	6.138	1	11.076
	44	1.170	1	1.291	1	9.542	1.234	1	11.476
	49	0.330	0.282	0.285	0.220	5.492	0.335	0.271	5.859
	55	0.560	1	0.646	1	8.347	0.569	1	9.795
	56	0.260	0.464	0.205	0.317	4.724	0.265	0.465	6.108
4	17	1.060	1	1.481	1	11.843	1.146	1	11.259
	18	1.050	0.99	0.838	0.566	6.771	1.165	1.016	7.326
	45	0.700	1	0.645	1	7.104	0.723	1	7.519
	48	0.470	0.671	0.589	0.913	8.675	0.490	0.677	8.627
	24	0.530	0.101	0.922	0.176	12.456	0.540	0.096	11.003
	25	5.270	1	5.216	1	12.293	5.612	1	10.373
5	26	0.500	0.105	0.766	0.158	10.766	0.535	0.106	10.075
	27	4.770	1	4.846	1	12.345	5.046	1	11.122
6	29	1.720	0.564	2.248	0.800	12.422	1.783	0.564	12.277
	30	3.050	1	2.798	1	9.995	3.185	1	9.309
7	32	1.720	1	1.965	1	10.858	1.734	1	10.999
	33	1.330	0.773	1.220	0.620	8.209	1.356	0.773	7.495
8	35	0.720	1	0.859	1	9.186	0.732	1	8.818
	36	0.610	0.847	0.498	0.579	6.035	0.646	0.883	6.373

Table 8 Results of each corrected level in duct diameter and damper

Corrected Level	Duct Section	Duct Diameter (m)			Damper Angle	System Curve	Fan Operation Point	
		Original	Increase	Decrease			Pressure (Pa)	Flow Rate (m^3/sec)
1	2	0.873	1.00	–	–	$P = 4.067Q^2$	489.870	10.980
	39	0.539	0.54	–	29°			
2	3, 4, 5	0.269	–	0.20	–	$P = 3.811Q^2$	476.138	11.160
	6, 7	0.269	–	0.19				
	8, 9, 10, 11, 12, 13	0.858	1.00	–				
	42, 52, 54	0.362	0.41	–				
	53	0.362	0.42	–				
	43	0.458	–	0.45				
3	14, 15, 16	0.519	–	0.448	–	$P = 3.729Q^2$	470.156	11.235
	21, 22, 23	0.762	0.84	–				
	44	0.415	–	0.37				
	49, 50, 51	0.257	0.27	–				
	55	0.314	–	0.272				
4	17	0.519	–	0.36	–	$P = 3.725Q^2$	470.156	11.235
	18, 19, 20	0.397	0.45	–				
	45, 46, 47	0.340	0.35	–				
	48	0.294	–	0.269				
	24	0.307	–	0.25				
	25	0.735	0.83	–				
5	26	0.301	–	0.26	–	$P = 3.744Q^2$	471.365	11.220
	27	0.707	0.76	–				
6	29	0.480	–	0.43	–	$P = 3.780Q^2$	473.764	11.190
	30, 31	0.597	0.66	–				
7	32	0.480	–	0.448	–	$P = 3.803Q^2$	474.954	11.175
	33, 34	0.435	0.48	–				
8	35	0.345	–	0.325	–	$P = 3.780Q^2$	473.764	11.190
	36, 37, 38	0.324	0.36	–				

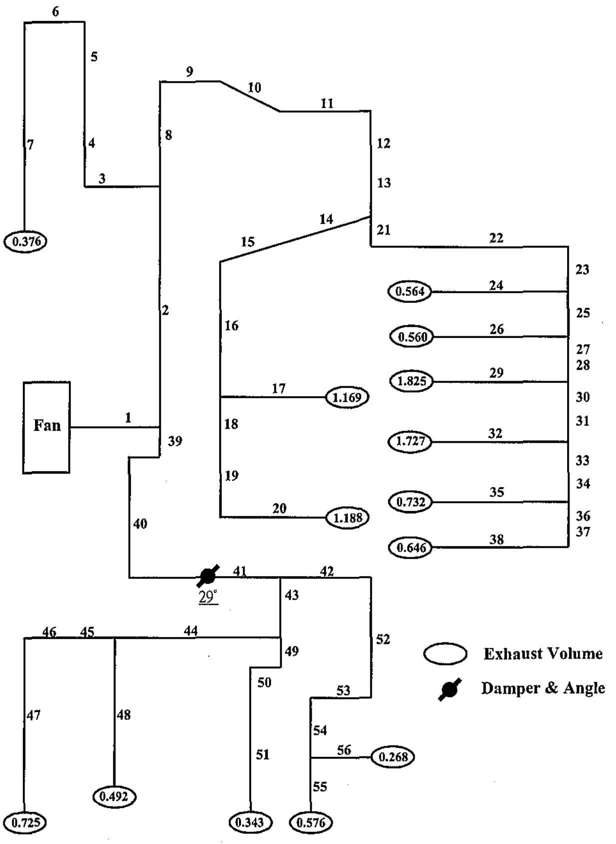

Fig. 6 System diagram from 3C duct design method

Figure 7 shows the correlation of average volume flow rate error between design values and correction results at each corrected level. Level 0 represents the results from initial simulation. Corrected levels 1 to 8 indicate correction results through computer-aided simulation at each correction process. Each level characterizes the feedback correction times in 3C duct design method. As the feedback correction is performing, the error is effectively reduced. Table 9 shows that the results of volume flow rate predicted from 3C duct design method is very close to those obtained from design requirements. The volume flow rate in initial computer simulation method (level 0), as compared with that at the original design requirements, has an average error around 42.68%. The volume flow rate predicted from the 3C design method (level 8) has an average error around 5.405%. It should be noted that the discrepancy in volume flow rate error for 3C duct design method is primarily because of system safety concerns in the design procedure. That is, a fan provide volume flow rate greater than the required volume flow rate to meet the demand of allowance of safety.

Table 10 shows the results of total surface area, fan total pressure and volume flow rate at each level's calculation. The designed duct total surface area diameter represents a system's initial cost. The total duct surface area is increasing from level 0 to corrected level 8. However, the change in surface area is very small. In other words, the adjustment made during design corrections had a very small impact on the initial cost of entire system. Thus, 3C design method can engage in refined corrections of the original design and achieve the volume flow rate without significantly altering the system itself. Besides, the values of fan total pressure and volume flow rate represent the energy cost of system operation. As shown in Table 10, the change of system volume flow rate is very limited. It should be noted that the fan total pressure increases around 3%. The reason for the rise in fan total pressure is due to the absence of a pressure-balancing device in initial design process. Dampers are added during design corrections, which increase the resistance and raise the fan total pressure as the number of corrections increases. The cost of entire system can be estimated based on construction cost and operating cost. From the above discussion 3C duct design method represents a very precise design method for designing a duct system.

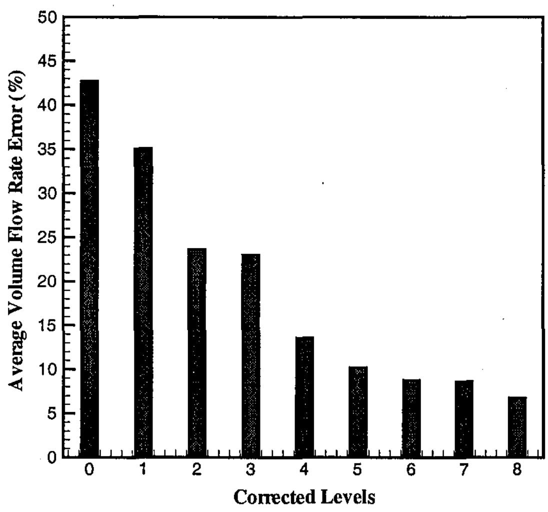

Fig. 7 Average volume flow rate error at each corrected level

Table 9 Comparison of design requirement, initial computer-aided simulation and 3C duct design method in volume flow rate

Duct Section	Design Requirement Flow Rate (m^3/sec)	Initial Computer-Aided Simulation (Level 0) Flow Rate (m^3/sec)	3C Duct Design Method Flow Rate (m^3/sec)
7	0.370	0.832	0.376
17	1.060	1.604	1.169
20	1.050	0.909	1.188
24	0.530	0.692	0.564
26	0.500	0.534	0.560
29	1.720	1.512	1.825
32	1.720	1.161	1.727
35	0.720	0.455	0.732
38	0.610	0.262	0.646
47	0.700	1.054	0.725
48	0.470	0.959	0.492
51	0.330	0.448	0.343
55	0.560	0.742	0.576
56	0.260	0.236	0.268

Table 10 Total surface area and fan capacity requirements in each corrected level

Corrected Level	Total Duct Surface Area (m^2)	Fan Total Pressure (Pa)	Fan Volume Flow Rate (m^3/sec)
Level 0	978.077	460.261	10.355
Level 1	993.240	489.870	10.980
Level 2	1011.823	476.138	11.160
Level 3	1021.444	470.156	11.235
Level 4	1030.769	470.156	11.235
Level 5	1028.102	471.365	11.220
Level 6	1027.591	473.764	11.190
Level 7	1026.429	474.954	11.175
Level 8	1029.830	473.764	11.190

After the loss coefficient database for duct devices is established, the computer program will automatically compute the loss coefficient. This saves designers the trouble of checking against related tables and figures all the time. As long as the program is accurate and the input data are correct, no mistake will occur in the computation results. Aided by high-speed computation, the time needed for the design can be substantially reduced. For example, T-simulation takes at least 20 calculation steps to finish a section. Given 100 sections in a system, it will take at least 8,000 calculation steps to finish the design. If conducted manually, it will take at least 50 hours to finish these calculations. 3C duct design method only takes 8 seconds by computer (tested via Pentium-90 CPU).

4. CONCLUSION

The case study presented in this paper shows that the application of 3C design method in duct system is feasible. During the design process, it often becomes necessary to change certain design parameters or alter the system layout due to limitations of the building's structure. In this case, designers simply change the computer input data to obtain new design results without spending considerable time in recalculation. If we consider to expand the existed exhaust facilities in duct system, the duct design is engaged in the simulation and correction processes. Designers can also conduct online system simulation during the design stage in order to find design flaws and correct them. Therefore, in addition to the design of a new exhaust system, the expansion of an existed duct system can also be considered.

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NOMENCLATURE

C : local loss coefficient
D : duct diameter [m]
K_S : sectional flow conductance coefficient [$m^3/s/Pa^{0.5}$]
$K_{S,sys}$: system flow conductance coefficient [$m^3/s/Pa^{0.5}$]
L : duct length [m]
P_{fan} : fan total pressure [Pa]
P_{sys} : system total pressure [Pa]
Q : duct airflow [m^3/s]
Q_{fan} : fan airflow rate [m^3/s]
Q_{sys} : system airflow rate [m^3/s]
T : proportional coefficient
ΔP : total pressure loss [Pa]
ΔP_{sys} : system pressure loss [Pa]
f : friction factor
ρ : air density [kg/m^3]

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