COMPUTER AIDED OPTIMAL DESIGN
OF DUCT SYSTEMS

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CHAPTER I

INTRODUCTION

General

One of the important problems related to the design of any ventilating or air conditioning system is being able to provide the best duct work. In order to achieve maximum energy efficiency and minimal duct material cost, the best design methods have to be chosen carefully. There are three methods described by the ASHRAE Handbook of Fundamentals (ASHRAE 1989) -- equal friction, static regain, and the T-method. Other methods mentioned by McQuiston (1989) are the balanced capacity and the velocity reduction methods. Among these standard methods, the T-method is the only method that claims to provide the optimal duct design.

The optimized duct design concept is based on minimizing the life cycle cost of the duct system. The duct system optimal design is a form of large scale optimization problem. There are several ways to solve this kind of multi-dimensional problem, but most of them cannot always find the globally optimal point. The T-method uses the ideas of dynamic programming optimization method. If used properly, the dynamic programming method has a good chance of finding the global minimum. Much research related to duct design has been done before by using the dynamic programming method (Shitzer 1979).

The method of simulated annealing (Kirkpatrick, 1983) is a relatively new general-purpose method of very large scale optimization, which has been attracting significant attention recently. It offers the possibility of finding the global optimal point. This method has been reported to be used in power distribution systems (Chiang et al., 1990), optical areas (Kim, 1990), image processing areas (Carnevali, 1985), electronics (Kirkpatrick, 1983), and biochemistry areas (Prabhakaran, 1985). It was reported to have solved the travelling salesman problem, and the global wiring problem of silicon chips successfully (Kirkpatrick,1983).

Although the T-method has successfully optimized duct network problems, it is unusual for one optimization method to work well for all problems. Also, the T-method has some limitations. For example, the T-method cannot solve problems with the velocity limit constraints and the static pressure limit constraints. This is one of the important reasons to look for alternatives to the T-method.

The purpose of this study is to apply the modified simulated annealing method to the duct system optimization problem and compare its results to the T-method. It is therefore necessary to implement the T-method.

Technical Background

A literature survey was done in the areas of duct design technology and large scale optimization.

Duct Design Methods

The equal friction method (McQuiston, 1988) is based on making the pressure loss per foot of duct length the same for the entire system. This method will produce a well balanced duct system if all runs of duct are the same. In most practical systems, this is not the case. The short runs will have to be damped to increase the resistance, which will result in a waste of energy.

The balanced capacity method (McQuiston, 1988) involves making the total pressure loss of each path the same under design flow rates. In general, this means that the longest path is sized first, and then the other paths are sized to have the correct pressure loss to match the total pressure at each junction. It is a natural law that all duct systems will balance themselves. The dampers may have to be installed to insure correct flow rates. The system will not be the optimal.

In 1940 Carrier et al. (Tsal, 1988) recommended the static regain duct design method. They thought that this method would be better than the equal friction and the velocity reduction methods. The static regain method saves energy by converting "kinetic energy" into static pressure. The duct section nearest the fan is sized first by using some additional criteria, and the remaining ducts are sized to have the same total pressure. McQuiston (1988) classified this method as a high velocity duct design method. This method is based on the Bernoulli-Borda equation below:

$$\Delta P = (\frac{V_1^2}{C} - \frac{V_2^2}{C}) - (\frac{k(V_1-V_2)^2}{C}) \qquad (1.1)$$

V_1, V_2 --- velocity of air in the duct (m/s).

C --- fitting coefficient.

k --- gradual/abrupt expansion loss ratio

This method was critiqued by Tsal et al. (1988). Other disadvantages were discussed by McQuiston (1988).

The velocity reduction method (Tsal, 1986) can be represented below:

$$V_{j+1} = u\, V_j\,, \quad j = 1,2,\ldots,n-1 \qquad (1.2)$$

u --- Reduction factor.

V --- Velocity of the air (m/s).

j --- The number of duct section.

The velocity reduction method is used primarily for variable air volume systems (VAV), which depends on the VAV boxes to balance the system pressure loss. It consisted practically of making sure that the duct closest to the fan has acceptable velocity, and then reducing the velocities of the downstream ducts so that the velocities are reduced gradually. This method is some what heuristic and requires a sound background of duct design experience.

The constant velocity method (Tsal, 1986) is a special case of the velocity reduction method, where the reduction factor is 1.0 The velocities of the whole system remain the same. The T-method's starting point is based on this method.

T-method

The T-method is a special method for duct network optimal design. It uses the ideas of dynamic programming. Because of the complexity of the duct network and its constraints, most of the methods mentioned above are not capable of finding the global minimum of the duct network cost (Tsal, 1987). Dynamic programming has a better chance to find the global minimum.

The first trial of using dynamic programming in duct system design optimization was by Tsal et al. in 1968 (Tsal, 1987). Arkin and Shitzer had also published their works about using dynamic programming design of the duct system (Arkin, 1979). Tsal et al. tried to optimize the velocity of the duct by dynamic programming (1986). They took the first partial derivatives of the objective function, which is always the life cycle cost of the duct network, with respect to velocity for each section of the duct network (Tsal, 1986, Equation 20) to form several equations. They calculated the optimum air velocity of each duct section by solving these partial derivative equations.

In 1989 when the T-method was introduced, the optimum pressure loss ratio is calculated by taking the partial derivatives of the objective function with respect to pressure losses (Tsal, 1989, Equation 1.24). The system is balanced when the fan pressure is distributed optimally by the ratios of T factors which are calculated by using the partial derivatives of the objective function. T factors are the fan pressure distribution factors introduced by Tsal. T factors are calculated by condensing the system into one node. After the fan is selected the fan pressure is distributed by expanding the system. If the system is not balanced, the iteration is needed. This method seems to find the global minimum of the life cycle cost of the duct network. More detailed discussions are made in the following chapter.

Other Optimization methods

There are several ways to optimize the duct network which have been tried before--the Coordinate Descent Method (Tsal, 1987), Lagrange Multipliers Method (Tsal, 1987), Reduced Gradient Method (Abadie,1969), Quadratic Search Method (Leah, 1987), and Dynamic Programming (Bellman, 1957). These methods were well explained by Tsal and Adler (1987).

Simulated Annealing Method.

Kirkpatrick (1983) developed a stochastic optimization procedure which is analogous to the statistical thermodynamics of the annealing process of the heated metal with the optimization methods. First, the system is heated up, then cooled down, and then the temperature is kept at the annealing point for a long time, so that the atoms will line themselves up to form a pure crystal. The pure crystal often contains less energy and has less defects.

By simulating the thermodynamics problem, the introduced pseudo-temperature is the control parameter of the process. When the temperature is high, atoms move in all directions. When the iteration begins, the objective function is allowed to go uphill. The lower the temperature, the longer the iteration will last. Therefore, there is less chance for the system to go in an uphill direction. The possibility for the objective function to go uphill is controlled by the Metropolis Monte Carlo function. The new move is accepted or not with the possibility that its objective function is lower than before, or with the probability $\exp(-\Delta E/T)$ if the objective function is higher than before. Simulated annealing provides the possibility of finding the global minimum.

CHAPTER II

T-METHOD IMPLEMENTATION

Introduction

The T-method is an optimal fan pressure distribution method. The pressure ratio of two duct sections connected in series are calculated by taking the partial derivative of the objective function with respect to pressure losses.

Objective function

Tsal (1989) uses life cycle cost as his objective function.

$$E = E_p * (PWEF) + E_s \tag{2.1}$$

where

E = life cycle cost of the duct system ($).

E_p = annual electric energy cost ($).

E_s = Initial cost of the duct system ($).

PWEF = present worth escalation factor.

Electric energy cost:

$$E_p = Q_{fan} \frac{(E_c)\, Y + E_d}{10^5\, \eta_f\, \eta_e} P_{fan} \tag{2.2}$$

where

Q_{fan} = total air flow rate(m^3/s).

E_c = unit energy cost (\$/kWh).

Y = system operation time (hr/year).

E_d = energy demand cost (\$/kWh).

P_{fan} = Fan pressure (Pa.).

η_f = fan total efficiency.

η_e = motor total efficiency.

Initial Cost:

$$E_s = S_d \pi D L \quad \text{(Round ducts)} \tag{2.3}$$

$$E_s = 2 S_d (H+W) L \quad \text{(Rectangular ducts)} \tag{2.4}$$

where

S_d = unit duct work cost (\$/m^2).

Present Worth Escalation Factor:

$$PWEF = \frac{[(1+AER)/(1+AIR)]^{a} - 1}{1 - [(1+AIR)/(1+AER)]} \tag{2.5}$$

AER = annual escalation rate.

AIR = average interest rate.

a = amortization period.

The objective function can be written in the form of coefficient K, which is the duct characteristic defined by Tsal (1989).

The duct characteristic coefficient K can be calculated by

$$K = n (\mu)^{0.2} Q^{0.4} L \tag{2.6}$$

n parameter is

$$n=1 \quad \text{(Round)} \tag{2.7}$$

$$n=\frac{1+r}{(\pi\ r)^{0.5}} \tag{2.8}$$

where

$$r = \frac{\text{Height}}{\text{Width}} \tag{2.9}$$

μ ---- coefficient

$\mu = f\ L + C\ D$ (round)

$$\mu = \left(\frac{f\ L}{D_f} + C\right) D_v \quad \text{(Rectangular)} \tag{2.10}$$

where

L = length of the duct (m).

C = fitting coefficient.

f = friction coefficient.

Q = air flow volume(m^3/s).

r = aspect ratio for rectangular duct.

D_f ---- equivalent-by-friction diameter (m).

$$D_f = \frac{2\ H\ W}{H + W} \tag{2.11}$$

D_v ---- equivalent-by-velocity diameter (m)

$$D_v = 1.128\ (\ H^*W\ )^{1/2} \tag{2.12}$$

where

H = height of the rectangular duct (m).

W = width of the rectangular duct (m).

From the above equation Tsal found the final objective function. (Tsal, 1989).

$$E=z_1(P_{fan}\ ) + z_2\ K\ (\Delta P)^{-0.2} \tag{2.13}$$

K ---- duct characteristic coefficient

z_1, z_2---- Intermediate variable z_1, z_2:

$$z_1 = Qfan \frac{(E_c)\,Y}{10^5 \eta_e \eta_f} (PWEF) \tag{2.14}$$

$$z_2 = 0.959\,\pi \left(\frac{\rho}{g}\right)^{0.2} S_d \tag{2.15}$$

T-method's objective function is reasonable, clear, easy to understand, and easy to take the partial derivatives.

T Factor

The T-method uses the ideas of the dynamic programming optimization method and other traditional optimization methods. Its optimization relies on the partial derivatives of the objective function. The T-method's objective function can be written as follows, if the duct system has two duct sections connected in series:

$$E = E_1 + E_2 \tag{2.16}$$

E_1, E_2 = the life cycle cost of each section.

The relationship of pressure losses is

$$\Delta P = \Delta P_1 + \Delta P_2 \tag{2.17}$$

$\Delta P_1, \Delta P_2$ = pressure loss of each section (Pa.).

In order to calculate the optimal fan pressure distribution factor, the partial derivative of the objective function is taken with respect to ΔP_1 and ΔP_2, and set equal to zero.

$$\frac{\partial E}{\partial(\Delta P_1)} = z_1 - 0.2\ z_2 K_1\ (\Delta P_1)^{-1.2} = 0$$

$$\frac{\partial E}{\partial(\Delta P_2)} = z_1 - 0.2\ z_2 K_2\ (\Delta P_2)^{-1.2} = 0 \tag{2.18}$$

where

K_1, K_2 --- intermediate variables (duct characteristic coefficient).

From the partial derivative equations above, we can get the optimal pressure loss ratio of two sections connected in series.

$$\frac{\Delta P_1}{\Delta P_2} = (\frac{K_1}{K_2})^{0.833} \tag{2.19}$$

Take the reciprocal of each side and add 1 to each side of equation (2.19).

$$\frac{\Delta P_2}{\Delta P_1} + 1 = \left(\frac{K_2}{K_1}\right)^{0.833} + 1 \tag{2.20}$$

From equation (2.20)

$$T = \frac{\Delta P_1}{\Delta P_1 + \Delta P_2} = \left(\frac{K_1^{0.833}}{K_1^{0.833} + K_2^{0.833}}\right) \tag{2.21}$$

T = T factor of T-Method, the optimal ratio of the pressure losses for two duct sections.

The T factor is calculated by taken the partial derivatives of the objective function. It is the heart of the T-method, which is the optimal fan pressure distribution factor of the two sections or equivalent sections connected in series. T factor is calculated by finding the K coefficients of every duct sections.

Pressure loss is calculated by the Darcy-Weisbach equation for round and rectangular ducts.

Round:

$$\Delta P = (\frac{f L}{D} + C)\frac{V^2 \rho}{2 g} \qquad (2.22)$$

Rectangular:

$$\Delta P = (\frac{f L}{D_f} + C)\frac{V^2 \rho}{2 g} \qquad (2.23)$$

ρ = Air density (kg/m^3).

g = constant (1.0 kg-m/(N-s^2).

Using μ coefficient:

Round: $\Delta P = 0.811\ g^{-1}\mu\ \rho\ Q^2 D^{-5}$ 2.24)

Rectangular: $\Delta P = 0.811\ g^{-1}\mu\ \rho\ Q^2 D_v^{-5}$ (2.25)

To express the diameter in terms of a pressure loss:

$$D_v = 0.959(\mu\ \rho)^{0.2}\ Q^{0.4}\ (g\ \Delta P)^{-0.2} \qquad (2.26)$$

If two duct sections are connected in parallel, there is no pressure distribution problem, just is a balancing problem. T-method just set the pressure losses of these two sections equal.

From previous equations, the equivalent-by-cost diameter D_o can be calculated for rectangular duct section.

$$D_O = 2(H+W)/\pi \tag{2.27}$$

So

$$D_o = \frac{1+r}{\sqrt{\pi r}} D_v = n * D_v \qquad \text{(Round n=1)} \tag{2.28}$$

The initial cost of duct E is

$$E_S = \pi * D * L * S_d$$

$$= 0.959(\mu\ \rho)^{0.2} * Q^{0.4} * (g\,\Delta P)^{-0.2}\, n\, L \tag{2.29}$$

Then, the K coefficient can be calculated alternately:

$$K = n\, \mu^{0.2}\, Q^{0.4}\ L \tag{2.30}$$

K factor or coefficient of each duct section can be calculated by condensing the whole system into one node.

Condensing

Next is the process of condensing two duct sections connected in series into one node.

$$K_{1\text{-}2}=(K_1^{0.833} + K_2^{0.833})^{1.2} \tag{2.31}$$

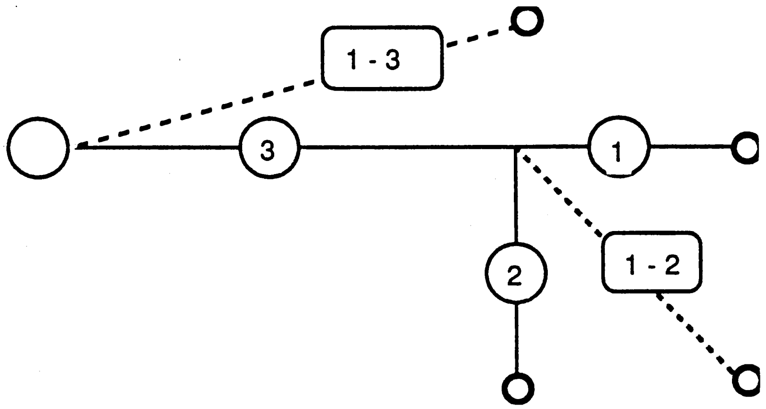

Figure 1. Condensing a tee.

Condensing a tee is shown in Figure 1 which contains one node, two children in parallel, and one parent in series:

$$K_{1-3}=(K_{1-2}{}^{0.833}+ K_3{}^{0.833})^{1.2} \tag{2.32}$$

$$=[(K_1+K_2)^{0.833} + K_3{}^{0.833}]^{1.2} \tag{2.33}$$

From equation 2.33

$$E = z1(P_{fan}) + z2\ K\ (\Delta P)^{-0.2} \tag{2.34}$$

The optimum fan pressure can be calculated by taking the derivative of Equation 2.34 with respect to ΔP, setting to zero, and solving for pressure loss.

$$P_{fan(opt)} = 0.26\ (\frac{z2}{z1}\ K)^{0.833} + \Delta P_{max} \tag{2.35}$$

ΔP_{max} ----- Maximum additional pressure loss (Pa.).

If fan and motor are preselected, the existing fan pressure is treated as optimum.

Expansion

This step distributes fan pressure through the system proportional to the T coefficients or T factors.

Duct pressure loss

$$\Delta P_i=(P_i)T_i \tag{2.36}$$

$$\text{Tee coefficient} \qquad T=\left(\frac{K_i}{K_{i-1}}\right)^{0.833} \tag{2.37}$$

$K_i = K_S$ at duct section #i.

So

$K_S = K_i$

We call K_{1-i} of node #i K_t. K_t is the K for condensed node.

$$T=\left(\frac{K_s}{K_t}\right)^{0.833} \tag{2.38}$$

So we can calculate the pressure loss for each node.

$$\Delta P = P * T \tag{2.39}$$

P is the pressure at that node. By knowing ΔP, we can find out the optimized duct diameter:

$$D=0.959\ (\mu\ \rho)^{0.2}\ Q^{0.4}\ (g\ \Delta P)^{-0.2} \tag{2.40}$$

$$\frac{2(H + W)}{\pi} = D \quad \text{for rectangular duct} \tag{2.41}$$

After the D is calculated, the pressure loss of each duct is calculated, then the pressure loss of each path is calculated. If the maximum pressure loss of every path is greater than 4 percent different (Tsal, 1989) (or the other percentage) from the fan pressure, iteration is needed. Using the duct diameter D estimated by previous function, the previous calculation can be done again and again until the pressure loss is balanced.

CHAPTER III

NUMERICAL STUDY OF DUCT DESIGN METHOD

Introduction

As discussed before, when air flow of each duct section is specified, the duct design involves two major problems. When two duct sections are connected in parallel, there is a pressure balancing problem. When two duct sections are connected in series (Figure 2), there is a pressure distribution problem. Almost all the duct design methods are concerned with these two problems. The way to calculate the pressure distribution ratios in each method is different and is not always obviously observed. The following paragraphs are going to discuss how the pressure distribution ratios are calculated by different duct design methods.

Two Sections Connected in Series

Fan pressure can be distributed by introducing the fan pressure distribution factor (FPDF). If two ducts are connected in series (Figure 2), the pressure ratio of these two duct sections can be represented below

$$\frac{\Delta P_1}{\Delta P_2} = \text{FPDF}$$

or

$$\frac{\Delta P_1}{\Delta P_1 + \Delta P_2} = \text{FPDF}^* \qquad (3.1)$$

These two FPDFs are different in number but are the same in meaning.

where

ΔP_1 = pressure loss of first section (Pa.).

ΔP_2 = pressure loss of second section (Pa).

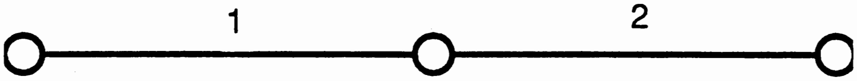

Figure 2. Two duct sections connected in series.

Total pressure loss:

$$\Delta P = \Delta P_1 + \Delta P_2 \qquad (3.2)$$

Two Sections Connected in Parallel

✓ If there are only these two sections in the system, their pressure losses have to be the same (Figure 3).

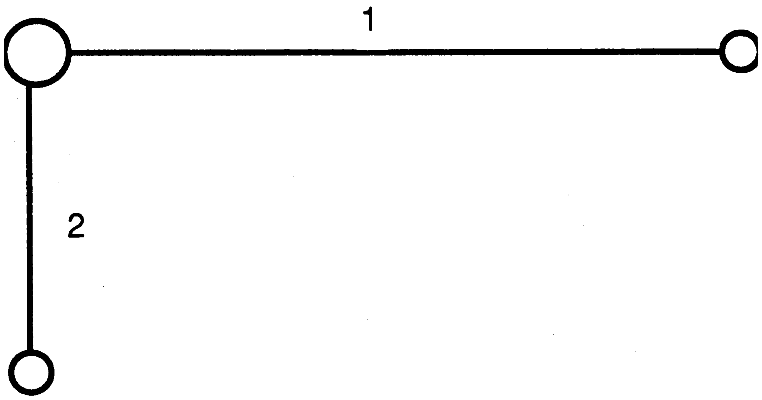

Figure 3. Two duct sections connected in parallel.

$$\Delta P = \Delta P_1 = \Delta P_2 \tag{3.3}$$

The concept of the imaginary section is based on the idea that one subtree of ducts can be viewed as one large imaginary duct section.

The following sections will try to collapse the existing duct design methods, or duct optimization methods into one formula.) ✓

T-Method

T-method is an optimization method which uses the T factor. T factor is the fan pressure distribution factor. The fan pressure distribution factor (FPDF*) can have any value between zero and one, and the system will still be balanced. The T-method has its own way to calculate the fan pressure distribution factor, given by equation (2.21). In this section, it will be shown that the T-method for determining the T-factor can also be cast as a method which sets the fan pressure distribution factor equal to a ratio of initial costs.

$$FPDF^{*} = T = \frac{\Delta P_1}{\Delta P_1 + \Delta P_2} = \frac{E_{s1}}{E_{s1} + E_{s2}} \tag{3.4}$$

Using the technique shown in equations (2.19) through (2.21)

$$\frac{\Delta P_1}{\Delta P_2} = \frac{Es_1}{Es_2} \tag{3.5}$$

The mathematical analysis is shown below.

The initial cost of one duct section is

$$E_S = \pi * D * L * S_d$$

$$= 0.959\ (\mu\ \rho)^{0.2} * Q^{0.4} * (g\,\Delta P)^{-0.2} n\,L \tag{3.6}$$

Substituting (3.6) into (3.5) yields

$$\frac{\Delta P_1}{\Delta P_2} = \frac{E_{s1}}{E_{s2}} = \frac{0.959\ (\mu_1 \rho)^{0.2}\ Q_1^{0.4}\ (g\ \Delta P_1)^{-0.2}\ n_1\ L_1}{0.959\ (\mu_2 \rho)^{0.2}\ Q_2^{0.4}\ (g\ \Delta P_2)^{-0.2}\ n_2\ L_2} \tag{3.7}$$

ΔP_1, ΔP_2 --- Optimal pressure drops of two duct sections connected in series.

Equation (3.7) simplifies to

$$\frac{\Delta P_1}{\Delta P_2} = \frac{n_1 (\mu_1)^{0.2}\ Q_1^{0.4}\ (\Delta P_1)^{-0.2}\ L_1}{n_2 (\mu_2)^{0.2}\ Q_2^{0.4}\ (\Delta P_2)^{-0.2}\ L_2} \tag{3.8}$$

solving (3.8)

$$\frac{\Delta P_1}{\Delta P_2} = \left(\frac{n_1\ (\mu_1)^{0.2}\ Q_1^{0.4}\ L_1}{n_2\ (\mu_2)^{0.2}\ Q_2^{0.4}\ L_2} \right)^{0.833} \tag{3.9}$$

from equation (2.30)

$$K = n\mu^{0.2}\, Q^{0.4}\;\; L \qquad (3.10)$$

Substitute equation (3.10) into equation (3.9)

$$\frac{\Delta P_1}{\Delta P_2} = \left(\frac{K_1}{K_2}\right)^{0.833} \qquad (3.11)$$

Using the technique shown in equations (2.19) through (2.21)

$$FPDF^* = T = \frac{\Delta P_1}{\Delta P_1 + \Delta P_2} = \left(\frac{K_1^{0.833}}{K_1^{0.833} + K_2^{0.833}}\right) = \frac{E_{s1}}{E_{s1} + E_{s2}} \qquad (3.12)$$

Therefore, we reach T-Method's result. Thus, the assertion that the T-factor can also be represented as a ratio of the initial costs is true. This ratio will control the fan pressure distribution to each duct section.

Equal Friction Method

This method is purely a duct design method without involving any optimization method. The FPDF of this method is equal to the ratio of lengths of two sections connected in series.

This method is based on sizing each duct so that the pressure loss per unit total length is constant.

$$\frac{\Delta P_1}{L_1} = \frac{\Delta P_2}{L_2} = \ldots = \frac{\Delta P_n}{L_n} \qquad (3.13)$$

From the formula above, the fan pressure distribution factor of section one can be calculated as

$$FPDF^* = \frac{\Delta P_1}{\sum_{i=1}^{n} \Delta P_i} = \frac{L_1}{\sum_{i=1}^{n} L_i} \quad (3.14)$$

This means the equal friction method can be represented in the FPDF* factor.

Balanced Capacity Method

Balanced Capacity Method is similar to the equal friction method. The difference is that fan pressure distribution factors (FPDF*) are calculated by the longest equivalent length of the subtree.

$$FPDF^* = \frac{L_1}{\text{Longest (path1,path2, ..., pathj)}} \quad (3.15)$$

Velocity Reduction Method

The velocity is reduced by the u factor.

$$\frac{V_1}{V_2} = u \quad (3.16)$$

Recall Darcy-Weisbach equation

$$\Delta P = f \frac{Le\ V^2}{D} \frac{\rho}{2g} \quad (3.17)$$

Le --- Equivalent length (m).

From equation 3.16 and 3.17, we get

$$\frac{\Delta P_1}{\Delta P_2} = \frac{f_1 * Le_1 * \frac{(V_1)^2}{(D_1 * 2g)} \rho}{f_2 * Le_2 * \frac{(V_2)^2}{(D_2 * 2g)} \rho} \qquad (3.18)$$

or

$$\frac{\Delta P_1}{\Delta P_2} = \frac{\frac{f_1 * Le_1 *}{(D_1)}}{\frac{f_2 * Le_2 *}{(D_2)}} * \left(\frac{V_1}{V_2}\right)^2 \qquad (3.19)$$

Equation 3.19 can be written this way

$$\frac{\Delta P_1}{\Delta P_2} = \frac{\frac{f_1 * Le_1}{(D_1 1)}}{\frac{f_2 * Le_2}{(D_2)}} * (u)^2 \qquad (3.20)$$

This means that the velocity reduction method can be described by using the FPDF factor.

Conclusion

Most of the duct design method can be represented in the calculation of fan pressure distribution factor. The different methods have different FPDF factors. Therefore, they have different results.

CHAPTER IV

NUMERICAL PROCEDURE AND ANALYSIS OF OPTIMAL PRESSURE DISTRIBUTION METHOD

Duct system optimization methods should be capable of finding the minimum of the system cost, balancing the system, selecting the fan, and distributing the fan pressure to the system properly.

The basic idea of optimal pressure distribution (OPD) method balance the duct network pressure losses of each path, 2) to select the optimal fan pressure, and 3) to distribute the fan pressure in the proportion of the optimal pressure distribution ratio. The optimal pressure distribution ratios are chosen by the modified simulated annealing method rather than calculated by T-method.

OPD Factor

We borrowed the T-Method's ideas of optimizing the ratios of the pressure losses of the duct sections instead of optimizing the velocities or the pressure losses directly. We call these ratios Fan Pressure Distribution Ratios. Although the purpose of duct optimization is to find the optimal duct sizes, we cannot optimize the duct sizes explicitly. The sizes of duct sections are dependent on each other because the pressure losses of each paths have to be balanced. In order to provide simulated annealing method independent variables, the OPD factor is introduced. OPD factor is the ratio of pressure losses of two duct sections or one duct section and a duct subtree.

Consider a two sections duct system where the fan pressure has already been selected. If two ducts are in parallel, there is a balancing problem. These two sections have to have the same pressure losses. There is no optimization problem if the fan pressure has already been chosen. If two ducts are in series, there is no balancing problem, but there is a pressure distribution problem. The cost of the system is related to how the fan pressure is distributed. This is an optimization problem.

In OPD method, the optimum pressure ratio is

$$\frac{\Delta P_1}{\Delta P_2 + \Delta P_1} = \mathrm{OPDF} \tag{4.1}$$

where

ΔP_1, ΔP_2 -- The pressure losses of first and second section in series (Pa.).

OPDF -- Optimal Pressure Distribution Factor.

The fan pressure can be calculated as

$$P_{fan} = \Delta P_1 + \Delta P_2$$

If there are only two duct sections or one duct and one subtree of ducts in the system.

Objective Function

We borrowed T-method's objective function, for the purpose of comparison. The objective function includes the initial cost and the energy cost of the system.

The objective function is

$$E = E_p\,(PWEF) + E_s \qquad (4.2)$$

Electric energy cost:

$$E_p = Q_{fan}\,\frac{(E_c)\,Y + E_d}{10^5\,\eta_f\,\eta_e}\,P_{fan} \qquad (4.3)$$

Present Worth Escalation Factor (PWEF):

$$PWEF = \frac{[(1+AER)/(1+AIR)]^{\,a} - 1}{1 - [(1+AIR)/(1+AER)]} \qquad (4.4)$$

AER = annual escalation rate (%).

AIR = annual interest rate (%).

a = amortization period (year).

The initial cost (Es) can be calculated as

$$E_s = S_d\,\pi\,D\,L \qquad \text{(Round)} \qquad (4.5)$$

$$E_s = 2\,S_d\,(H+W)\,L \qquad \text{(Rectangular)} \qquad (4.6)$$

where

D = duct diameter (m).

H = duct height (m).

W = duct width (m).

η_f = fan efficiency (%).

η_e = fan motor efficiency (%).

P_{fan} = fan pressure (Pa.).

Q_{fan} = fan flow rate (m^3/s).

The related economic factors can be estimated from the following sources (Tsal, 1989):

Duct price per unit (S_d)---"Sheet Metal Estimating"
Annual escalation rate (AER)---"Utility Costs Forecasting"
Amortization period (a) --- Expected Life time of duct system.
Energy demand cost (E_d) --- "Electric Power Annual"
Energy unit cost (E_c) --- "Electric Power Annual"

The life cycle cost E is calculated one by one of each duct section. The total cost is calculated by adding all the E_s together. The fitting cost, fan cost, heating and cooling coil cost are considerate as constant, and not included in the objective function.

Fundamental Equations

The basic equation is the Darcy-Weisbach Equation. The total pressure loss of the flow in closed duct can be calculated as follows: (Wright,1945)

$$\Delta P = f \frac{L}{D}\frac{V^2}{}\frac{\rho}{2g} \qquad (4.7)$$

where

ΔP = head loss due to friction (Pa.).

L = conduit length (m).

D = conduit inside diameter (m).

V = fluid velocity (m/s).

g = acceleration due to gravity (1.0 kg-m/N-s^2).

ρ = air density (kg/m^3)

f = friction factor.

Because the air velocity is relatively low, the air flow rate can be calculated as

$$Q = V * A \qquad (4.8)$$

Q = air flow rate (m^3/s).

A = area of the duct cross-section (m^2).

From equation 4.8, the following relationship can be found:

$$V = \frac{4}{\pi}\frac{Q}{D^2} \qquad (4.9a)$$

$$V = Q/(H * W) \qquad (4.9b)$$

For rectangular ducts, the duct width can be interpreted in terms of an equivalent-by-velocity diameter by equating Equations 4.9a and 4.9b.

From 4.7 and 4.9, the equivalent-by-velocity diameter can be calculated

$$D_v = \left(\left(\frac{4}{\pi}\right)^2 f\,Le * \rho\,(2g\,\Delta P)^{-1}\,Q^2\right)^{1/5} \tag{4.10}$$

where

D_V = equivalent-by-velocity diameter (m).

Le = equivalent length (m).

ΔP = pressure loss of this duct section (Pa).

π = 3.1415926535898

For the rectangular duct

$$V = Q / (H * W) \tag{4.11}$$

From equation 4.9 and 4.11, we can get the equivalent velocity diameter D_V of the rectangular duct section:

$$D_v = \sqrt{\left(\left(\frac{4}{\pi}\right) * H * W\right)} \tag{4.12}$$

and the equivalent-by-friction diameter for the rectangular duct is:

$$D_f = 2 * \left(\frac{H * W}{H + W}\right) \tag{4.13}$$

We can also find the following relationship.

$$W = \pi\,\frac{D^2}{4\,H} \tag{4.14}$$

Reynold's number is

$$Re = \frac{D_f * V}{\mu} \tag{4.15}$$

where

μ = viscosity.

By using Altshul's equation (Tsal,1989), we can calculate friction factor

$$f = 0.11 \left(\frac{\varepsilon}{D_f} + \frac{68}{Re}\right) \qquad (4.16)$$

ε = roughness of the duct material.

Pressure balancing is a natural law of all duct systems. If the designers do not balance the system, the system will balance itself. In which case the air flow of each duct will be different than the designed flow rate. Some room probably has too much of a supply of air, but some room does not have enough supply of air.

If the system (Figure 4) is balanced, three equations have to be satisfied (ASHRAE, 1989).

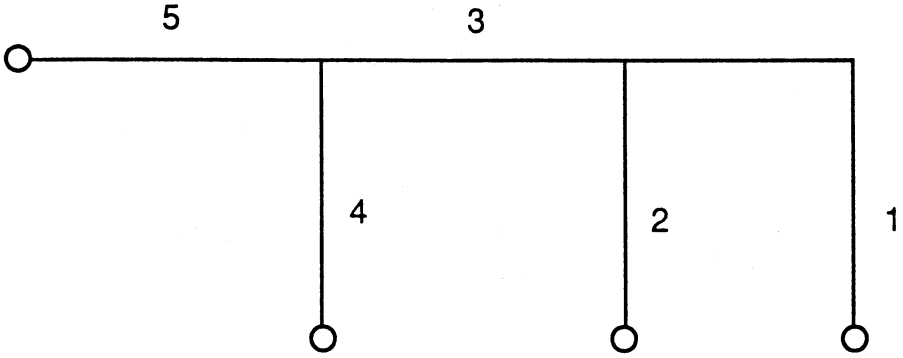

Figure 4. Five duct sections system.

$$\Delta P_1 = \Delta P_2$$

$$\Delta P_4 = \Delta P_3 + \Delta P_2$$

or $$\Delta P_4 = \Delta P_3 + \Delta P_1$$

$P_{fan} = \Delta P_5 + \Delta P_3 + \Delta P_1$

or $P_{fan} = \Delta P_5 + \Delta P_3 + \Delta P_2$

or $P_{fan} = \Delta P_4 + \Delta P_5$

The optimal system should not rely on the damper to balance the pressure. The ducts should be sized properly in order to have the appropriate pressure losses.

The fan pressure is distributed as the ratios of optimal pressure distribution factor (OPDF), where the OPD factor is selected by simulated annealing method.

$$\Delta P_i = OPDF_i \left(P_{fan} - \sum_{Root}^{Present\ section} \Delta P \right) \tag{4.17}$$

i = the duct section number of each path.

ΔP_i = the pressure losses of each section.

The optimal pressure distribution factor is first calculated by

$$OPDF_i = \frac{Le_i}{\sum_{Present}^{Leaf\ of\ Subtree} Le} \tag{4.18}$$

Le_i = equivalent length of number i section.

$\sum Le$ = the longest equivalent length of the tree.

Because of the definitions above, all OPDFs are independent themselves. If you change one, the rest do not have to change, and the system will still be balanced. So the simulated annealing method is able to change the OPD factor without unbalancing the system.

The total equivalent length equals

$$Le = L + D * C / f \qquad (4.19)$$

Le = equivalent length (m).
D = diameter of the duct (m).
C = loss coefficient.
f = friction factor.
L = the original length of the duct (m).

Optimization Procedure

OPD method's optimization procedure is much different than the T-method. It starts from choosing the OPDF factors of the duct system. The computer uses a random number generator to determine which OPDF factors should be changed, and which directions the OPDF should change. If the OPDF picked by computer cannot be changed (Terminal node, presized section or the other constraints) or the direction of the change is wrong, another set of random numbers will be needed. After the OPDF is changed, new duct sizes are calculated, and a new life cycle cost of the duct system is calculated. If this new life cycle cost is lower than the previous one, the change will be kept. If the new life cycle cost is higher than the previous one, the change is kept with the possibility of exp(-

$\Delta E/T$). T is the pseudo-temperature introduced by simulated annealing method. T will become smaller and smaller until there are no more changes being accepted. The final life cycle cost of the system is the result.

Fan Pressure Optimization

The fan pressure is calculated differently than the T-method. The fan pressure is not calculated by simulated annealing also. It is calculated by one dimensional minimization method called the Golden Search Method. The relationship between fan pressure and the system life cycle cost is different than the duct sizes. So one dimensional optimization procedure is used to find out the optimal fan pressure. The golden search is used to find out the optimum fan pressure. If the fan has already selected, the fan should work at the maximal efficient point, that pressure should be the optimum fan pressure. If the fan pressure is given by the user, it will not be changed during the optimization.

CHAPTER V

DUCT TREE DATA STRUCTURE

The optimal fan pressure distribution method was calculated in C computer language. C gives more feasibility to design those very complex and very large systems. The tree structure programmed in C makes the programming much more logical than the spread sheet.

Tree presentation

The tree like duct system can be presented in tree data structure. The physical connection between two duct sections can be represented in logical connection between two data structures. So a tree structure of duct network can be exactly duplicated in the machine memory. This will benefit the simulation of duct system.

Data Structure of "DUCT TREE"

The data structure of one duct section is represented as below.

```
typedef struct duct_section {
    double V,L,Q,DPz,Dz,C,Df,Dv,D;
    double f,DP,DPmax;
    double Pup,Pdn,DPt,DPr,DPp;
```

```
  double Le,OPDF;
  double H,W;
    int ch1,ch2,presized;
    } duct_section;
```

It contains most of the important information of this duct section for further calculation or output.

Also there is a shell or connecter for this duct section data structure.

```
typedef struct node {
    int i;
    duct_section *D;
     struct node *prev;
     struct node *ch1;
     struct node *ch2;
   } node;
```

It contains a pointer to the duct section, a duct number, a pointer to the previous duct section, and two pointers to the child sections.

Traversal of Duct Tree

Theoretically, traverse of the tree can be done in two ways: depth first traverse and breadth first traverse. Breadth first traverse searches the node in a certain depth --- a certain number of layers. This has nothing to do with the physical duct system. So we use the other way, depth first traverse. It depends on if the children are processed first, or parents are processed first. The depth first traversal of duct tree can be classified in preorder, inorder, and postorder. Preorder traversal of the tree precesses the parent node first, and then goes to the children node. Postorder is the reverse.of the preorder. The parent node is processed last, the child nodes are processed first. The inorder traversal of the data structure tree processes the nodes from left to right (or from right to left). If the calculation starts from fan to terminals, the preorder traversal of the duct tree is the best choice. If the calculation starts from terminal to fan, the postorder traversal of the duct tree is needed.

Recursion, which uses the hardware stack, is faster than the iteration method, and the source code is shorter also. Therefore we used the recursive function to traverse the duct tree.

Preorder Traversal

The fan pressure should be distributed from the duct section closest to the fan to the terminal or from root to leaf. A preorder traversal of the duct tree is needed. A preorder traversal example shown below is a function called recursive which calculates the pressure loss of each duct section.

```
dstri_pres(H,Pfan)
node *H;
double Pfan;
{
double Dv5,f,Q,Le,dP;
```

```
 if(H == NULL)
    return;

 if(H->D->presized != TRUE)
     H->D->DP = Pfan * H->D->OPDF;

 f = H->D->f;
 Le = H->D->Le;
 Q = H->D->Q;
 dP = H->D->DP - H->D->DPz;

 if(dP <= 0.0)
   dP = 0.01;

 Dv5 = 16./(PI * PI) * f * Le
      * DENSITY * (Q * Q)/(2. * GC * dP);

 if(H->D->presized == FALSE)
    H->D->Dv = pow(Dv5,0.2);

  dstri_pres(H->ch1,(Pfan - H->D->DP));
  dstri_pres(H->ch2,(Pfan - H->D->DP));
}
```

Postorder Traversal

The biggest pressure loss of each path of the duct network should be calculated from the terminal to fan or from leaf to root. A postorder traversal of the duct tree network is used. This function is a recursive function and returns a value of biggest pressure loss of the whole duct network.

```
double  calc_DP(H,DP,biggest)
node *H;
double  DP,biggest;
{

   if(H == NULL)
      return(max(biggest,DP));

    biggest = calc_DP(H->ch1,H->D->DP + DP,biggest);
    biggest = calc_DP(H->ch2,H->D->DP + DP,biggest);

    if((H->ch1 == NULL)&&(H->ch2 == NULL))
      biggest = max(biggest, DP);
     return(biggest);
}
```

CHAPTER VI

RESULTS, DISCUSSIONS AND CONCLUSIONS

The mathematical model developed in this work was programmed using C language. The computer program worked under both DOS and UNIX system, on both IBM 386 and RISC System 6000. This program is capable of minimizing the life cycle cost of both rectangular and round duct systems. Another program was developed to implement the T-method for comparison.

Both of these two programs can solve the supply-return system problems. Both programs have solved the example problem in the ASHRAE Handbook of Fundamental 1989 and Tsal's Five duct sections example problem. The computer output can be found in the Appendix.

Results of Simulated Annealing

From Figure 5 to Figure 8, the plots show how the simulated annealing method worked to minimize the life cycle cost of the ASHRAE example problem. The modified simulated annealing method started from the results of balanced capacity method. The air velocities shown on the figures are the air velocities of the longest paths of the system.

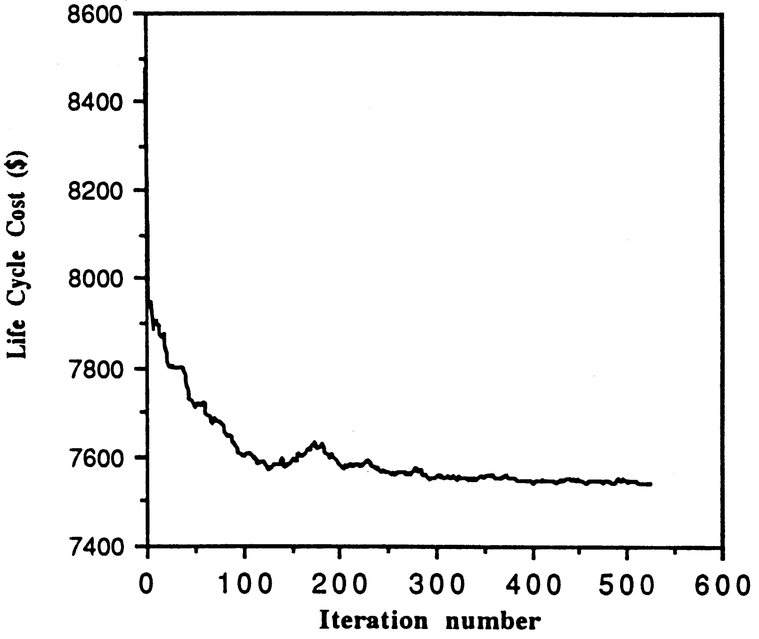

Figure 5. ASHRAE Example (V=7.5 m/s)

In ASHRAE example, because the fan is preselected both the life cycle cost of the duct system and the total duct surface areas can be the objective function. They have a constant relation.

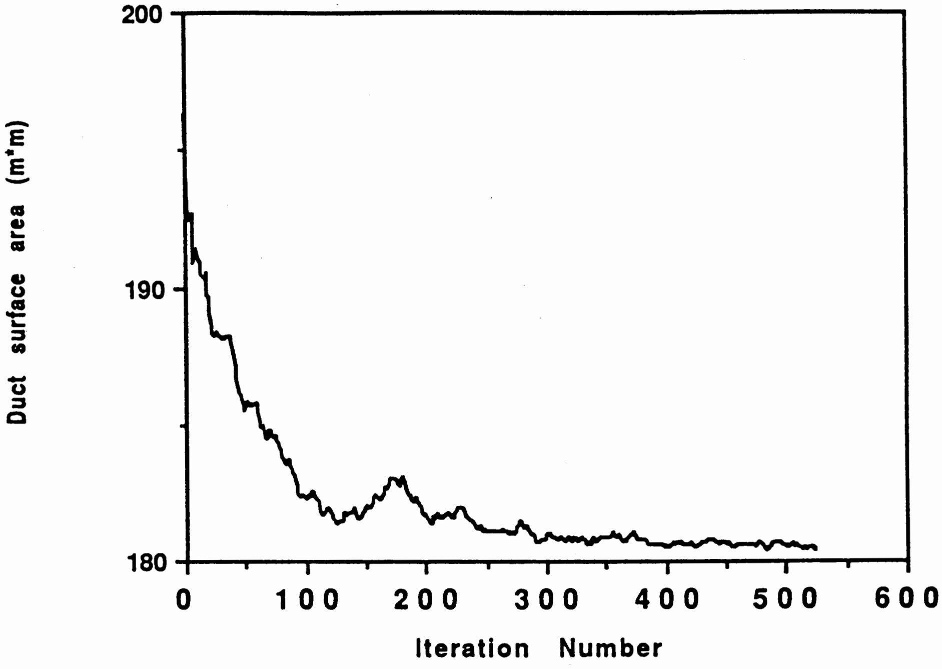

Figure 6. ASHRAE Example (V = 7.5 m/s)

A different starting point was used to test if the lowest life cycle cost of the duct system has any relationship with the starting point.

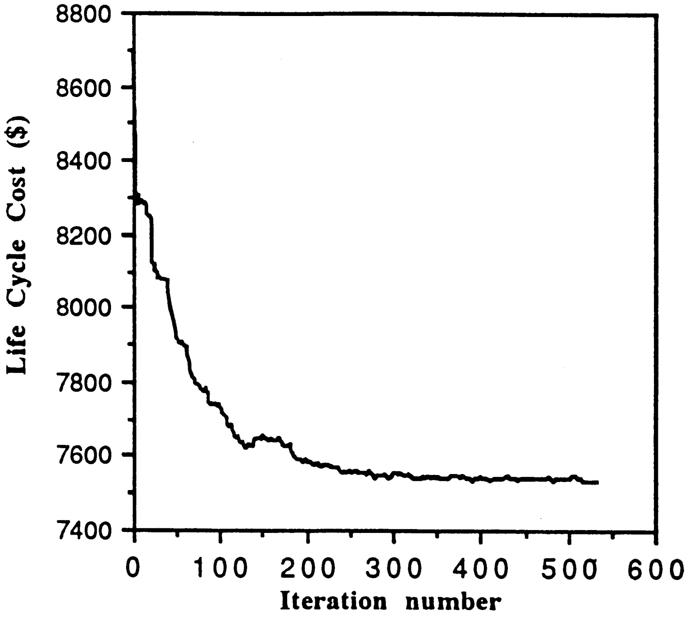

Figure 7. ASHRAE Example (V = 4.5 m/s)

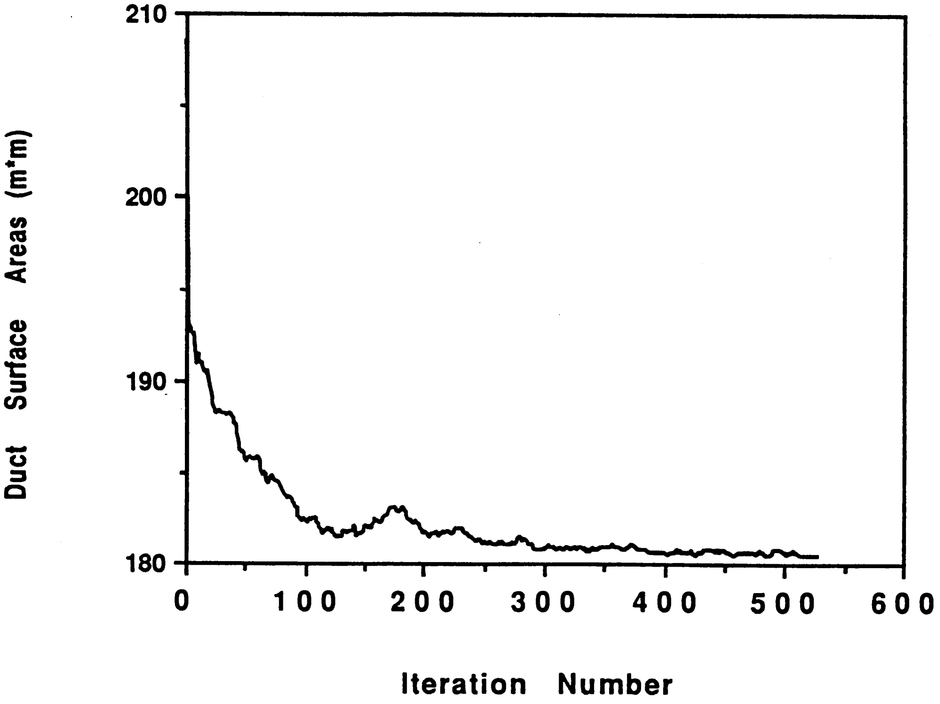

Figure 8. ASHRAE Example (V = 4.5 m/s)

We found that the lowest cost has nothing to do with the starting point. The objective function started from different starting points and terminated at the same result.

We observed the significant changes of the total duct surface areas, of the ASHRAE example (Figure 5 and Figure 7). And also we found that the objective function and the total duct surface areas has a very close relationship. Because the fan pressure is preselected, the duct surface areas are actually the objective function.

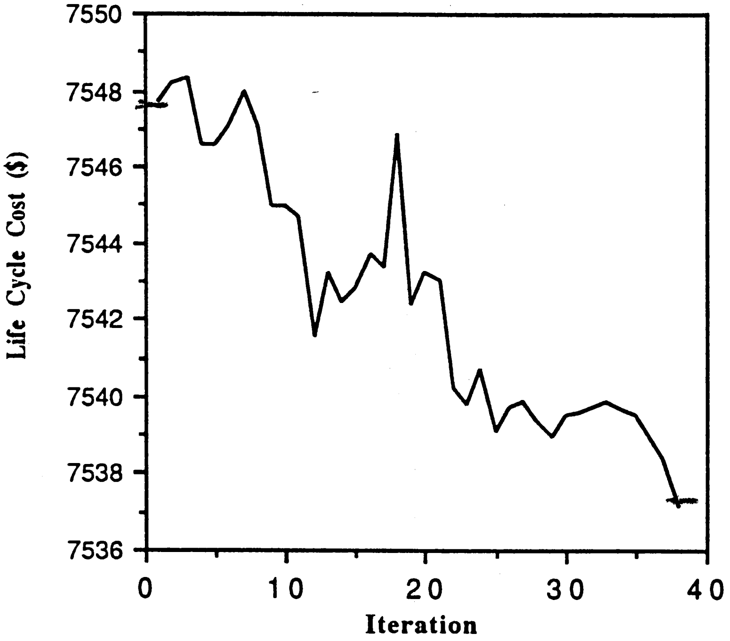

Figure 9. ASHRAE Example Final Calculation (V = 7.5 m/s)

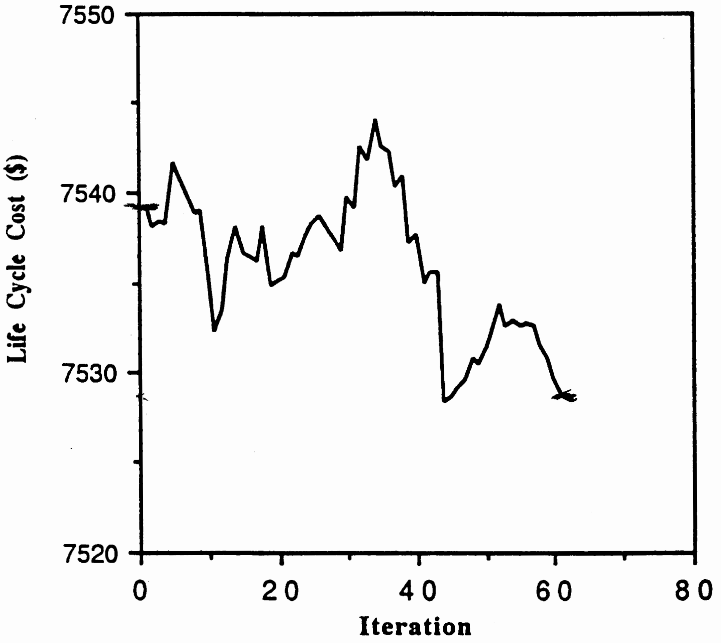

Figure 10. ASHRAE Example Final Calculation (V=4.5m/s)

Figure 9 and Figure 10 are the detailed analyses of the annealing procedures. We can see that the objective function oscillated violently even at the final stage of the calculation. Perspectively, the objective function moved towards the global minimum. It started at $8692 and ended at $7528. The duct surface area reduced from 211 square meters to 180.12 square meters. The surface area is 14.8% smaller than the ASHRAE handbook example (211 square meters).

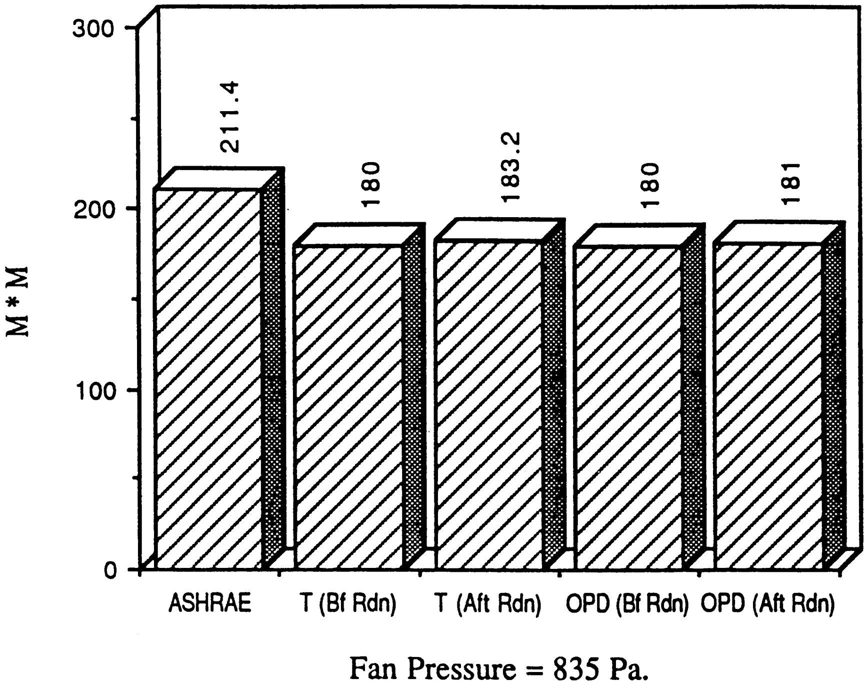

Figure 11. Duct Surface Area of Different Design Method.

Figure 11 shows the comparison of the OPD method, the T-method and the ASHRAE example. Because the fan pressures used by different methods are the same, the duct surface areas can represent the cost of the system, which is the objective function. "Aft Rd" and "Bf Rd" stand for "After rounding" and "Before Rounding". We noticed the size rounding does not make too much difference of the total duct surface area.

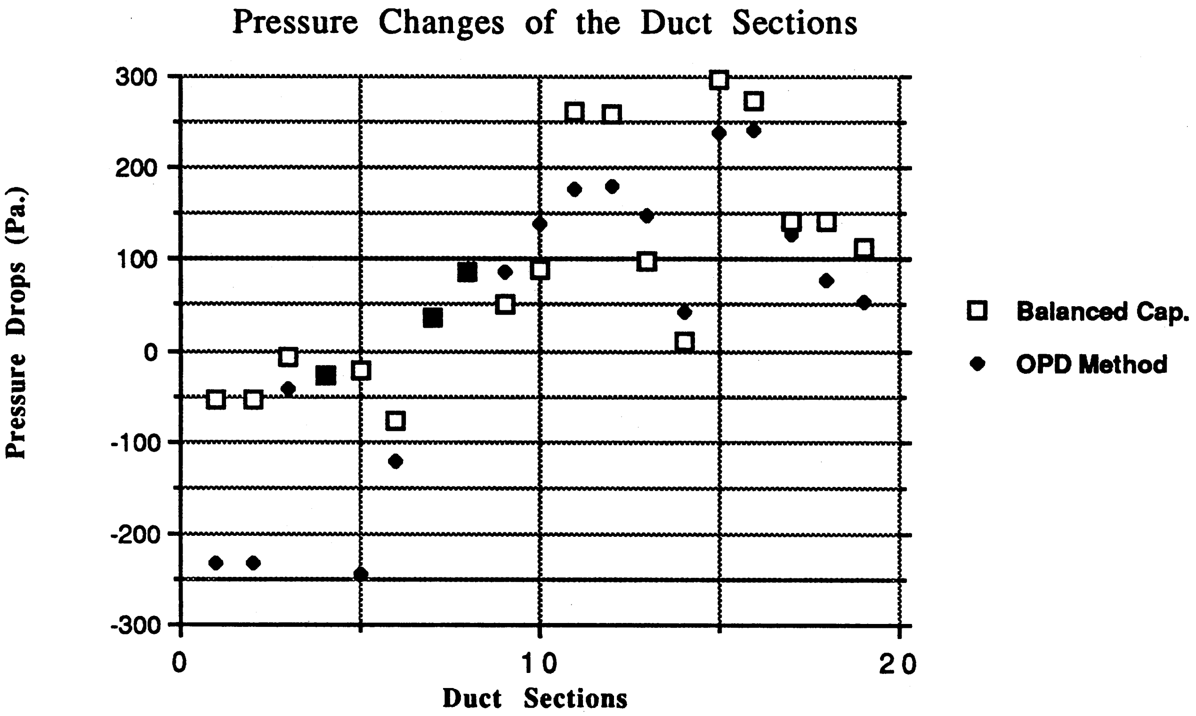

Figure 12. Pressure Changes of the Duct Sections.

Figure 12 shows the changes of pressure loss of each duct section. The OPD method is compared with the equal capacity method which is the starting point of the OPD method. The negative pressure losses refer to the return duct sections. The preselected duct sections' pressure losses are kept the same during the calculation.

Results of Golden Search Method

The golden search method was used to find out the optimum fan pressure. It solved an example problem given by Tsal (1989). The result is presented in Figure 13 and Figure 14. The life cycle cost went down quickly and stopped at the bottom of the objective function while the fan pressure changed.

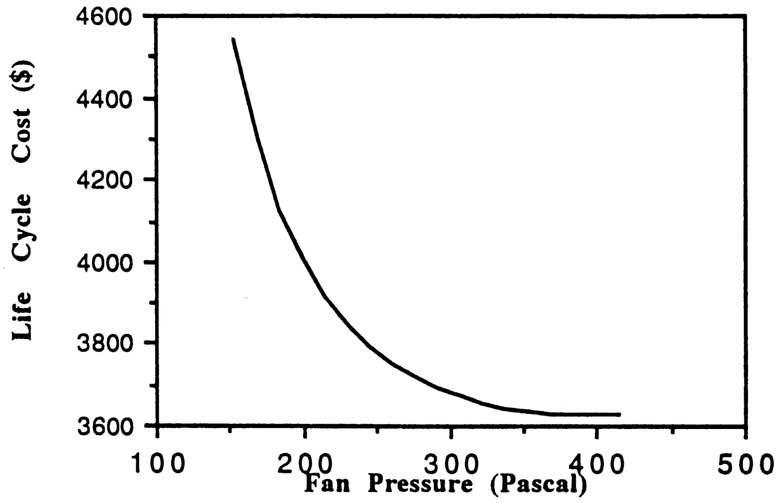

Figure 13. Life Cycle Cost vs. Fan Pressure
Five Sections Ductwork.

Figure 13 shows when the fan pressure increases the objective function goes down hill. But from a detailed look of the iteration, we will find that the objective function will goes uphill if we continue to increase the fan pressure (Figure 14).

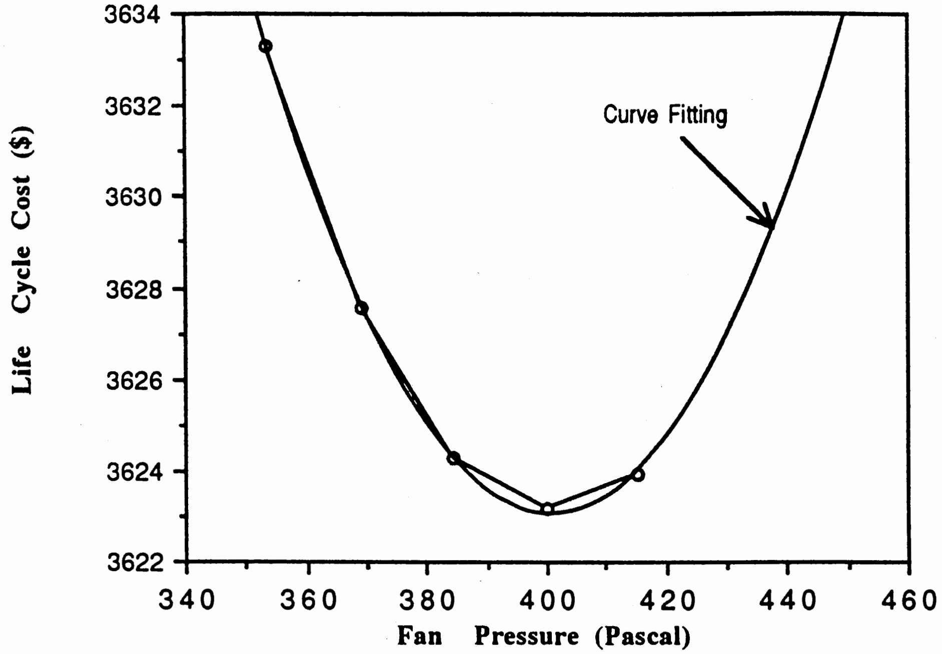

Figure 14. Details of Cost vs. Fan Pressure
Five Section Ductwork.

The computer program stopped at the lowest point of the pressure-cost curve. In this Five Duct Sections problem, if we continue to increase fan pressure, the life cycle cost of the duct system will increase rapidly.

Comparison of Pressure Losses

Without changing the fan pressure, how is the duct material saved? The answer is the fan pressure distributed more optimally. The pressure saved by the shorter duct sections which have the relatively high fitting resistance is used to shrink the longer duct sections' diameters. We can find the significant duct diameter changes are made by the computer programs in Figure 15.

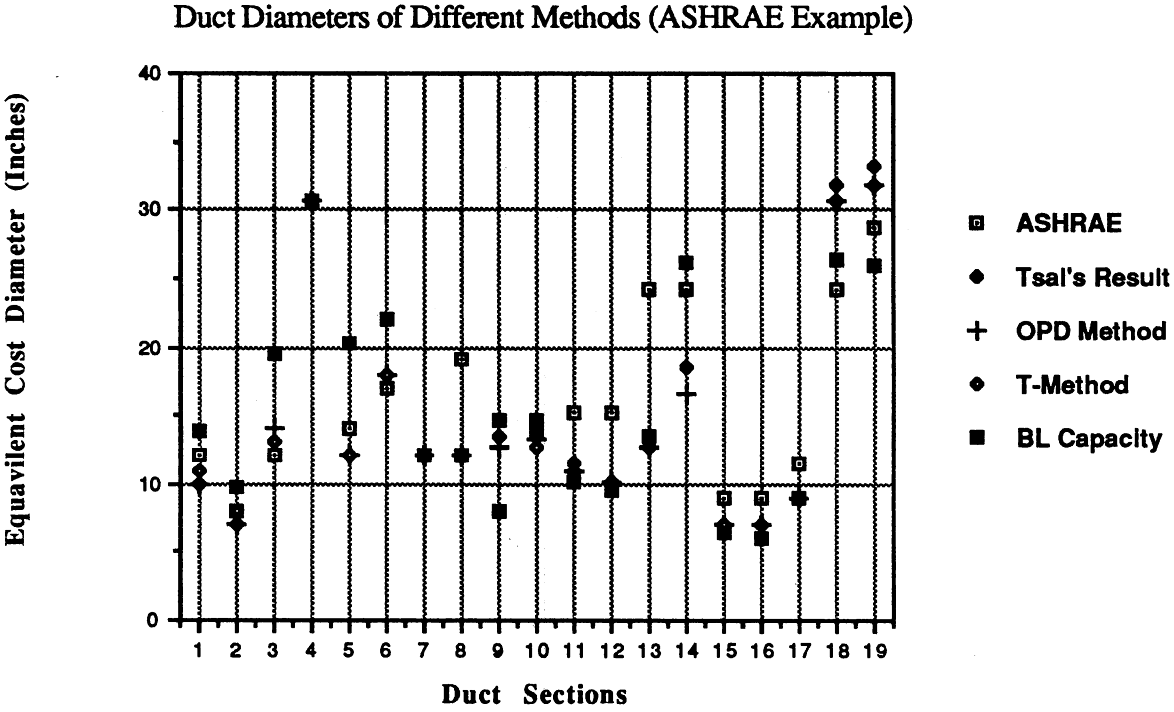

Figure 15. Duct Diameters of Different Methods
ASHRAE Example

The ASHRAE example problem was solved by T-method and the OPD method. We got little different results from Tsal's (1989) because we used different computer methods than Tsal. There is a round off error. There is a small difference between the T-method's results and OPD method's results. But they got the similar total duct surface areas (Figure 12). From Figure 15 we can see that the biggest pressure changes happened in the return duct sections. Most of the return duct sections have long lengths but less fitting frictions in ASHRAE example. An increase in the velocities of these duct sections can decrease the cross-sections of the ducts; therefore, the surface areas of the duct system will decrease. However, the increase of the pressure loss of the return system will decrease the velocity of the supply system, because the fan is fixed. We can see from Figure 15 that most of the duct pressure losses are reduced. Also we can find that not all of the duct pressure losses decreased. Sections 13 and 14 have relatively low fitting frictions compared to their lengths; therefore their pressure losses increase to reduce the surface area. Sections 18 and 19 have large fitting resistance but relatively short lengths; therefore the pressure losses at these two sections decline to save the energy for the other duct sections.

Comparison to T-Method

Both the T-Method and the OPD method can find the global minimum of the objective function. Their results validated each other. The T-Method has less iterations but relies on the partial derivatives of the objective function, and hence requires an objective function with analytically differentiable partial derivatives. The OPD method has more calculations but is more flexible to add constraints to without changing the mathematics model too much. Besides the constraints the T-Method can solve, the OPD method can solve the additional constraints, like air velocity limit, and static pressure limit or the other critical constraints. The changes required to add the new constraints to the software ~~are~~ small. It is more flexible to meet the future challenge of the new constraints brought by new control technology and the VAV system. Another improvement which the OPD method made is that the OPD method's objective function can be life cycle cost, or something else. Many kinds of economic analysis models can be used as the objective function. This gives the OPD method great advantage over T-method in business application.

Different Starting Point

We have tried to work on the same problem from different starting points. The results (Figure 5 and Figure 7) show that the simulated annealing method is able to reach the same answer (global minimum) from two different starting points.

Conclusions

Based on this study, the following conclusions have been developed:

(1) Both the OPD method and the T-method find essentially the same minimum of the objective function. The closeness of the minimum points strongly suggests that both methods have found the global minimum.

(2) As described by Tsal, the T-method has not been shown able to incorporate constraints such as air velocity limits or static pressure limits. Further more, it seems unlikely that such constraints

can be incorporated without fundamentally changing the method. The addition of a penalty function would add multiple singularities to the objective function, rendering the analytical partial derivatives indeterminate. On the other hand, the OPD method can easily incorporate such constraints.

(3) The OPD method's objective function is not limited to life cycle cost. It can be modified without changing the method itself. For example, the objective function could be the first cost of the system, including the fan.

(4) Most of the existing duct design methods can be cast as methods for determining the fan pressure distribution ratios of the ducts. This might be useful for future studies.

(5) The OPD method is a good alternative to the T-method.

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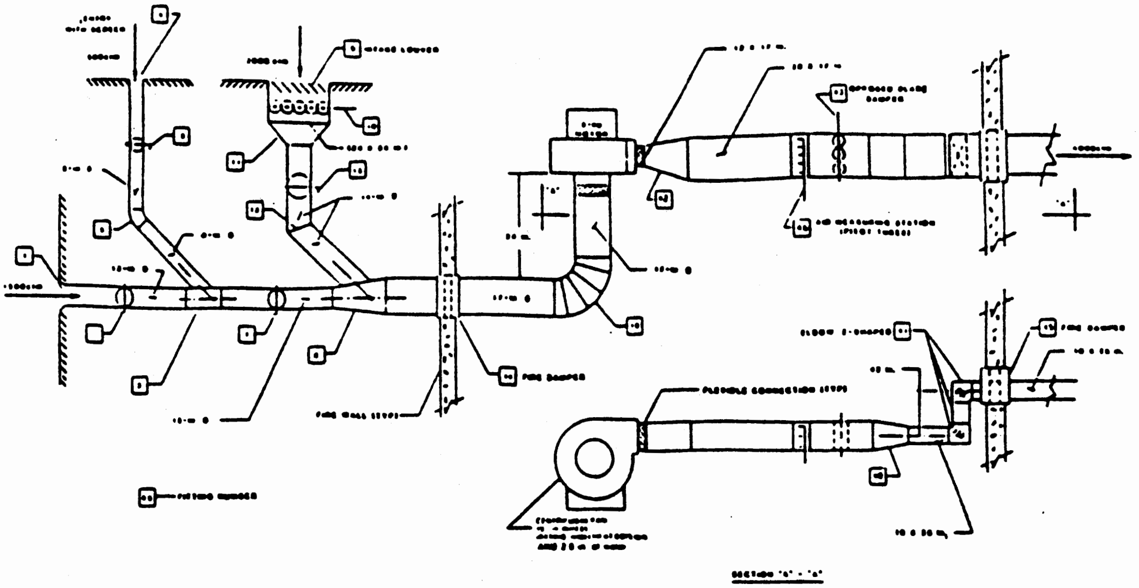
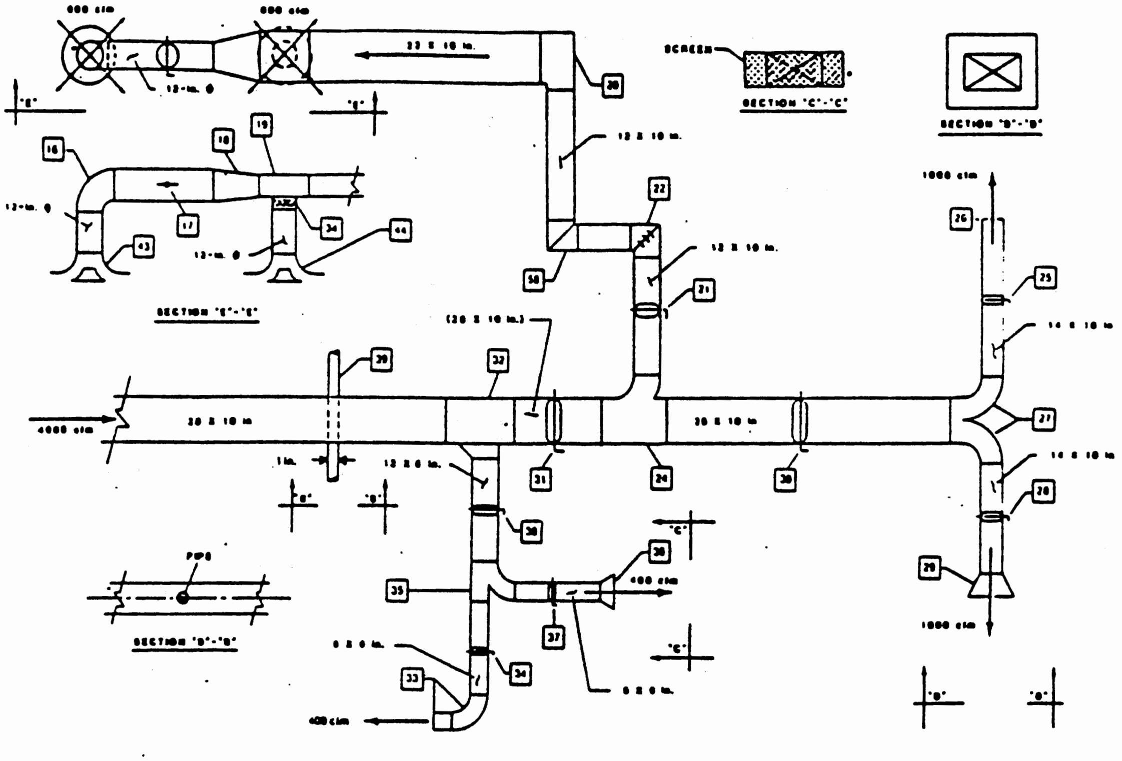
APPENDIXES

APPENDIX A

ASHRAE EXAMPLE SCHEMATIC


INTAKE LOUVER
FIRE DAMPER
FIRE WALL (TYP)
FITTING NUMBER
OPPOSED BLADE DAMPER
AIR MEASURING STATION (PITOT TUBES)
ELBOW Z-SHAPED
FLEXIBLE CONNECTION (TYP)
"A"
SECTION "A" - "A"


600 cfm
600 cfm
22 X 10 in.
12-in. Ø
"E"
"E"
SCREEN
SECTION "C"-"C"
SECTION "D"-"D"
16
18
19
17
43
34
44
12-in. Ø
12-in. Ø
SECTION "E"-"E"
20
12 X 10 in.
22
50
12 X 10 in.
21
1000 cfm
26
25
14 X 10 in
(20 X 10 in.)
29
32
4000 cfm
20 X 10 in
20 X 10 in
31
24
30
27
14 X 10 in
28
1 in.
12 X 6 in.
"B"
"B"
30
"C"
38
400 cfm
29
1000 cfm
PIPE
SECTION "B"-"B"
35
37
8 X 8 in.
34
33
400 cfm
8 X 8 in.
"C"
"D"
"D"

33. 17/4/87

APPENDIX B

ASHRAE EXAMPLE COMPUTER OUTPUT

OPD METHOD

T = 999.000000										
Node	1	2	3	4	5	6				
V	7.269	4.909	4.909	2.526	4.504	7.649				
OPDF	1	1	0.133	0	0.385	0.576				
Le	28.294	40.597	13.31	17.107	48.13	19.191				
L	24.38	23.77	7.31	1.52	20.42	11.89				
Q	0.71	0.24	0.94	0.94	0.94	1.88				
DPz	0	0	0	25	0	55				
Dz	0	0	0	0	0	0				
C	0.23	1.58	0.24	0.52	1.06	0.24				
Df	0.353	0.25	0.494	0.61	0.516	0.559				
Dv	0.353	0.25	0.494	0.688	0.516	0.559				
f	0.021	0.023	0.02	0.02	0.02	0.018				
DP	52.706	55.113	7.698	27.185	22.405	77.145				
DPmax	0	0	0	27.185	27.185	82.185				
ch1	0	0	1	0	4	3				
ch2	0	0	2	0	0	5				
D	0.353	0.25	0.494	0	0.516	0.559				
H	0	0	0	0.61	0	0				
W	0	0	0	0.61	0	0				
Plan = 836.000 E = 8692.5884 A = 215.012798										
T = 999.000000										
Node	7	8	9	10	11	12	13	14	15	
V	3.832	3.832	6.759	6.759	12.277	14.298	13.044	7.544	12.153	
OPDF	0	0	0.159	0.218	1	1	0.214	0.018	1	
Le	18.119	71.798	23.996	42.183	23.67	15.298	12.177	5.33	15.73	
L	4.27	1.22	7.62	13.72	9.16	6.71	10.67	4.57	9.75	
Q	0.28	0.28	0.56	0.56	0.47	0.47	0.94	1.51	0.19	
DPz	25	37.5	0	0	0	0	0	0	0	
Dz	0.305	0.305	0	0	0	0	0	0	0	
C	1.04	5.3	1.26	2.19	1.78	1.19	0.12	0.04	1.27	
Df	0.305	0.305	0.286	0.286	0.189	0.171	0.268	0.384	0.123	
Dv	0.305	0.305	0.325	0.325	0.221	0.205	0.303	0.505	0.141	
f	0.023	0.023	0.022	0.022	0.023	0.024	0.021	0.02	0.026	
DP	36.99	85.012	50.601	88.953	263.315	260.015	99.016	9.579	298	
DPmax	36.99	85.012	85.012	85.012	0	0	0	85.012	0	
ch1	0	0	7	9	0	0	11	10	0	
ch2	0	0	8	0	0	0	12	13	0	
D	0.305	0.305	0	0	0	0	0	0	0	
H	0	0	0.254	0.254	0.254	0.254	0.254	0.254	0.152	
W	0	0	0.326	0.326	0.151	0.129	0.284	0.788	0.103	
Plan = 836.000 E = 8692.5884 A = 215.012798										
T = 999.000000										
Node	16	17	18	19						
V	13.552	12.256	6.976	7.258						
OPDF	1	0.305	0.287	0.189						
Le	10.851	11.626	122.833	84.366						
L	6.1	9.14	7.01	3.66						
Q	0.19	0.38	1.88	1.88						
DPz	0	0	10	12.5						
Dz	0	0	0	0						
C	1.09	0.34	4.28	3.06						
Df	0.115	0.174	0.512	0.501						
Dv	0.134	0.199	0.586	0.574						
f	0.026	0.024	0.019	0.019						
DP	274.329	143.365	142.524	113.596						
DPmax	0	0	95.012	107.512						
ch1	0	15	14	16						
ch2	0	16	17	0						
D	0	0	0	0						
H	0.152	0.203	0.61	0.61						
W	0.092	0.153	0.442	0.425						
Plan = 836.000 E = 8692.5884 A = 215.012798										
T = 0.000000										
Node	1	2	3	4	5	6				
V	13.202	9.088	10.18	2.526	12.929	12.104				
OPDF	1	1	0.153	0	0.995	0.207				
Le	27.184	35.844	11.351	17.107	36.005	17.541				
L	24.38	23.77	7.31	1.52	20.42	11.89				
Q	0.71	0.24	0.94	0.94	0.94	1.88				
DPz	0	0	0	25	0	55				
Dz	0	0	0	0	0	0				
C	0.23	1.58	0.24	0.52	1.06	0.24				
Df	0.262	0.183	0.343	0.61	0.304	0.445				
Dv	0.262	0.183	0.343	0.688	0.304	0.445				
f	0.021	0.024	0.02	0.02	0.021	0.019				
DP	233.169	232.432	41.919	27.185	245.62	120.484				
DPmax	0	0	0	27.185	27.185	82.185				
ch1	0	0	1	0	4	3				
ch2	0	0	2	0	0	5				
D	0.262	0.183	0.343	0	0.304	0.445				
H	0	0	0	0.61	0	0				
W	0	0	0	0.61	0	0				
Plan = 395.053 E = 8692.5884 A = 180.114962										

T = 0.000000									
Node	7	8	9	10	11	12	13	14	15
V	3.832	3.832	8.623	8.276	10.284	12.189	15.257	14.488	11.089
OPDF	0	0	0.994	0.615	1	1	0.457	0.156	1
Le	18.119	71.798	22.096	39.447	25.47	16.394	12.049	5.186	16.111
L	4.27	1.22	7.62	13.72	9.16	6.71	10.67	4.57	9.75
Q	0.28	0.28	0.56	0.56	0.47	0.47	0.94	1.51	0.19
DPz	25	37.5	0	0	0	0	0	0	0
Dz	0.305	0.305	0	0	0	0	0	0	0
C	1.04	5.3	1.26	2.19	1.78	1.19	0.12	0.04	1.27
Df	0.305	0.305	0.255	0.26	0.211	0.19	0.248	0.314	0.129
Dv	0.305	0.305	0.288	0.294	0.241	0.222	0.28	0.364	0.148
f	0.023	0.023	0.022	0.022	0.023	0.023	0.022	0.02	0.026
DP	36.99	85.012	85.805	137.994	176.383	179.582	146.441	42.489	237.307
DPmax	36.99	85.012	85.012	85.012	0	0	0	85.012	0
ch1	0	0	7	9	0	0	11	10	0
ch2	0	0	8	0	0	0	12	13	0
D	0.305	0.305	0	0	0	0	0	0	0
H	0	0	0.254	0.254	0.254	0.254	0.254	0.254	0.152
W	0	0	0.256	0.266	0.18	0.152	0.243	0.41	0.113
Plan = 836.000 E = 8602.5884 A = 180.114962									

T = 0.000000				
Node	16	17	18	19
V	12.829	11.704	4.974	4.748
OPDF	1	0.351	0.201	0.114
Le	11.042	11.7	147.913	106.81
L	6.1	9.14	7.01	3.66
Q	0.19	0.38	1.88	1.88
DPz	0	0	10	12.5
Dz	0	0	0	0
C	1.09	0.34	4.28	3.06
Df	0.119	0.179	0.616	0.629
Dv	0.137	0.203	0.694	0.71
f	0.026	0.024	0.019	0.019
DP	240.507	127.716	76.705	55.362
DPmax	0	0	95.012	107.512
ch1	0	15	14	18
ch2	0	16	17	0
D	0	0	0	0
H	0.152	0.203	0.61	0.61
W	0.097	0.16	0.62	0.649
Plan = 836.000 E = 8602.5884 A = 180.114962				

T = 777.000000						
Node	1	2	3	4	5	6
V	13.202	9.088	10.18	2.526	12.929	12.104
OPDF	1	1	0.153	0	0.895	0.207
Le	27.184	35.844	11.351	17.107	36.005	17.541
L	24.38	23.77	7.31	1.52	20.42	11.89
Q	0.71	0.24	0.94	0.94	0.94	1.88
DPz	0	0	0	25	0	55
Dz	0	0	0	0	0	0
C	0.23	1.58	0.24	0.52	1.06	0.24
Df	0.262	0.183	0.343	0.61	0.304	0.445
Dv	0.262	0.183	0.343	0.688	0.304	0.445
f	0.021	0.024	0.02	0.02	0.021	0.019
DP	233.169	232.432	41.919	27.185	245.62	120.484
DPmax	0	0	0	27.185	27.185	82.185
ch1	0	0	1	0	4	3
ch2	0	0	2	0	0	5
D	0.254	0.178	0.356	0	0.305	0.457
H	0	0	0	0.61	0	0
W	0	0	0	0.61	0	0
Plan = 396.063 E = 7563.0100 A = 180.852790						

T = 777.000000									
Node	7	8	9	10	11	12	13	14	15
V	3.832	3.832	8.623	8.276	10.284	12.189	15.257	14.488	11.089
OPDF	0	0	0.994	0.615	1	1	0.457	0.155	1
Le	18.119	71.798	22.095	39.447	25.47	16.394	12.049	5.185	16.111
L	4.27	1.22	7.62	13.72	9.16	6.71	10.67	4.57	9.75
Q	0.28	0.28	0.56	0.56	0.47	0.47	0.94	1.51	0.19
DPz	25	37.5	0	0	0	0	0	0	0
Dz	0.305	0.305	0	0	0	0	0	0	0
C	1.04	5.3	1.26	2.19	1.78	1.19	0.12	0.04	1.27
Df	0.305	0.305	0.255	0.26	0.211	0.19	0.248	0.314	0.129
Dv	0.305	0.305	0.288	0.294	0.241	0.222	0.28	0.364	0.148
f	0.023	0.023	0.022	0.022	0.023	0.023	0.022	0.02	0.026
DP	36.99	85.012	85.805	137.994	176.383	179.582	146.441	42.489	237.307
DPmax	36.99	85.012	85.012	85.012	0	0	0	85.012	0
ch1	0	0	7	9	0	0	11	10	0
ch2	0	0	8	0	0	0	12	13	0
D	0.305	0.305	0	0	0	0	0	0	0
H	0	0	0.254	0.254	0.254	0.254	0.254	0.254	0.152
W	0	0	0.254	0.279	0.178	0.152	0.254	0.406	0.127
Plan = 836.000 E = 7563.0109 A = 180.852799									

T = 777.000000										
Node	16	17	18	19						
V	12.829	11.704	4.974	4.748						
OPDF	1	0.351	0.201	0.114						
Le	11.042	11.7	147.913	106.81						
L	6.1	9.14	7.01	3.66						
Q	0.19	0.38	1.88	1.88						
DPz	0	0	10	12.5						
Dz	0	0	0	0						
C	1.09	0.34	4.28	3.06						
Df	0.119	0.179	0.615	0.629						
Dv	0.137	0.203	0.694	0.71						
f	0.026	0.024	0.019	0.019						
DP	240.507	127.716	76.705	56.362						
DPmax	0	0	95.012	107.512						
ch1	0	15	14	18						
ch2	0	16	17	0						
D	0	0	0	0						
H	0.152	0.203	0.61	0.61						
W	0.127	0.152	0.61	0.66						
Plan = 835.000 E = 7553.0109 A = 180.852799										

APPENDIX C

FIVE DUCT SECTION PROBLEM COMPUTER OUTPUT

OPD METHOD

Five Duct Section Problem (OPD Method)

T = 999.000000						
Node	1	2	3	4	5	
V	5.639	4.001	10.756	8.771	4.001	
OPDF	1	1	0	1	0.373	
Le	26.452	19.284	10.899	24.015	73.728	
L	14	12	8	16	19.81	
Q	0.7	0.22	0.92	0.5	1.42	
DPz	25	37.5	0	0	37.5	
Dz	0	0	0.33	0	0	
C	0.8	0.65	0.18	0.65	1.5	
Df	0.334	0.265	0.33	0.269	0.672	
Dv	0.398	0.265	0.33	0.269	0.672	
f	0.021	0.024	0.02	0.022	0.019	
DP	57.423	54.024	46.98	89.888	57.196	
DPmax	25	37.5	84.48	0	121.98	
ch1	0	0	1	0	3	
ch2	0	0	2	0	4	
D	0	0.265	0.33	0.269	0.672	
H	0.254	0	0	0	0	
W	0.489	0	0	0	0	
Plan = 153.762 E = 4366.5629 A = 94.446611						

T = 0.000000						
Node	1	2	3	4	5	
V	13.214	11.136	10.756	13.914	8.11	
OPDF	1	1	0	1	0.329	
Le	22.258	16.198	10.899	22.176	56.892	
L	14	12	8	16	19.81	
Q	0.7	0.22	0.92	0.5	1.42	
DPz	25	37.5	0	0	37.5	
Dz	0	0	0.33	0	0	
C	0.8	0.65	0.18	0.65	1.5	
Df	0.229	0.159	0.33	0.214	0.472	
Dv	0.26	0.159	0.33	0.214	0.472	
f	0.022	0.025	0.02	0.023	0.019	
DP	250.902	224.127	46.98	271.115	128.316	
DPmax	25	37.5	84.48	0	121.98	
ch1	0	0	1	0	3	
ch2	0	0	2	0	4	
D	0	0.159	0.33	0.214	0.472	
H	0.254	0	0	0	0	
W	0.209	0	0	0	0	
Plan = 399.781 E = 3618.1754 A = 67.361296						

T = 777.000000						
Node	1	2	3	4	5	
V	13.214	11.136	10.756	13.914	8.11	
OPDF	1	1	0	1	0.329	
Le	22.258	16.198	10.899	22.176	56.892	
L	14	12	8	16	19.81	
Q	0.7	0.22	0.92	0.5	1.42	
DPz	25	37.5	0	0	37.5	
Dz	0	0	0.33	0	0	
C	0.8	0.65	0.18	0.65	1.5	
Df	0.229	0.159	0.33	0.214	0.472	
Dv	0.26	0.159	0.33	0.214	0.472	
f	0.022	0.025	0.02	0.023	0.019	
DP	250.902	224.127	46.98	271.115	128.316	
DPmax	25	37.5	84.48	0	121.98	
ch1	0	0	1	0	3	
ch2	0	0	2	0	4	
D	0	0.152	0.33	0.229	0.483	
H	0.254	0	0	0	0	
W	0.203	0	0	0	0	
Plan = 399.781 E = 3686.0462 A = 68.371062						

APPENDIX D

ASHRAE EXAMPLE COMPUTER OUTPUT

T-METHOD

ASHRAE Example Problem (T-Method)

Iteration 0

Node: 1	2	3	4	5	6
V: 7.500	7.5	7.5	2.526	7.5	7.5
L: 24.380	23.77	7.31	1.52	20.42	11.89
Q: 0.710	0.24	0.94	0.94	0.94	1.88
DPz: 0.00	0	0	25	0	55
Dz: 0.000	0	0	0	0	0
C: 0.230	1.68	0.24	0.52	1.06	0.24
Df: 0.347	0.202	0.399	0.61	0.399	0.565
Dv: 0.264	0.183	0.336	0.688	0.314	0.457
f: 0.019	0.019	0.019	0.019	0.019	0.019
DP: 52.80	128.864	19.838	27.172	68.565	76.601
mu: 0.54	0.77	0.235	0.39	0.811	0.361
Ks: 18.81	12.749	5.337	0	19.105	12.487
Kt: 18.81	12.749	40.361	0	19.105	79.396
T: 1.000	1	0.185	0	1	0.214
DPmax: 0.0	0	0	27.172	27.172	82.172
Pup: 208.0	208.038	255.341	27.172	255.341	372.487
Pdn: 0.00	0	208.038	0	27.172	255.341
DPt: 208.0	208.038	47.303	27.172	228.169	117.146
DPr: 208.0	208.038	47.303	0.1	228.169	62.146
ch1: 0	0	1	0	4	3
ch2: 0	0	2	0	0	5
DPp: 140.2	225.303	96.439	172.338	146.169	76.601
DPex: 223.2	147.184	0	200.149	0	0
D: 0.264	0.183	0.336	0	0.314	0.457
H: 0.000	0	0	0.61	0	0
W: 0.000	0	0	0.61	0	0

DPexmax = 223.240 Ep = 1519.761489 Es = 5621.984942

Pfan = 835.000 E1 = 7141.746 E2 = 7961.091 A = 192.785663

Node: 7	8	9	10	11	12	13	14	15	16
V: 3.832	3.832	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
L: 4.270	1.22	7.62	13.72	9.16	6.71	10.67	4.57	9.75	6.1
Q: 0.280	0.28	0.56	0.56	0.47	0.47	0.94	1.51	0.19	0.19
DPz: 25.00	37.5	0	0	0	0	0	0	0	0
Dz: 0.305	0.305	0	0	0	0	0	0	0	0
C: 1.040	5.3	1.26	2.19	1.78	1.19	0.12	0.04	1.27	1.09
Df: 0.305	0.305	0.273	0.273	0.25	0.25	0.335	0.385	0.159	0.159
Dv: 0.305	0.305	0.291	0.29	0.246	0.228	0.281	0.388	0.151	0.142
f: 0.019	0.019	0.019	0.019	0.019	0.019	0.019	0.019	0.019	0.019
DP: 36.50	84.875	60.455	106.196	83.542	57.353	24.452	8.967	82.185	61.39
mu: 0.39	1.64	0.552	0.97	0.699	0.48	0.289	0.134	0.437	0.327
Ks: 0.000	0	6.071	12.234	7.114	4.834	9.675	4.748	4.803	2.835
Kt: 0.000	0	6.071	20.824	7.114	4.834	24.816	54.068	4.803	2.835
T: 0.000	0	1	0.642	1	1	0.456	0.132	1	1
DPmax: 36.5	84.875	84.875	84.875	0	0	0	84.875	0	0
Pup: 84.87	84.875	165.252	309.379	168.254	168.254	309.379	343.435	195.443	195.443
Pdn: 48.3	0	84.875	165.252	0	0	168.254	309.379	0	0
DPt: 36.50	84.875	80.377	144.127	168.254	168.254	141.125	34.056	195.443	195.443
DPr: 36.50	0.1	80.377	144.127	168.254	168.254	141.125	34.056	195.443	195.443
ch1: 0	0	7	9	0	0	11	10	0	0
ch2: 0	0	8	0	0	0	12	13	0	0
DPp: 496.2	544.651	459.776	399.321	401.119	374.93	317.578	293.126	403.996	383.2
DPex: -33.7	-82.138	0	0	61.394	87.583	0	0	58.517	79.313
D: 0.305	0.305	0	0	0	0	0	0	0	0
H: 0.000	0	0.254	0.254	0.254	0.254	0.254	0.254	0.152	0.152
W: 0.000	0	0.294	0.294	0.247	0.247	0.493	0.793	0.167	0.167

DPexmax = 223.240 Ep = 1519.761489 Es = 5621.984942

Pfan = 835.000 E1 = 7141.746 E2 = 7961.091 A = 192.785663

Iteration 0

Node: 17	18	19
V: 7.500	7.5	7.5
L: 9.140	7.01	3.66
Q: 0.380	1.88	1.88
DPz: 0.00	10	12.5
Dz: 0.000	0	0
C: 0.340	4.28	3.06
Df: 0.224	0.491	0.491
Dv: 0.193	0.677	0.711
f: 0.019	0.019	0.019
DP: 37.65	163.604	120.554
mu: 0.28	2.57	1.808
Ks: 5.471	12.539	6.102
Kt: 15.024	89.544	101.12
T: 0.431	0.194	0.096
DPmax: 0.0	94.875	107.375
Pup: 343.4	415.795	462.513
Pdn: 195.4	343.435	415.795
DPt: 147.9	72.361	46.718
DPr: 147.9	62.361	34.218
ch1: 15	14	18
ch2: 16	17	0
DPp: 321.8	284.159	120.554
DPex: 0.00	0	0
D: 0.000	0	0
H: 0.203	0.61	0.61
W: 0.250	0.411	0.411

DPexmax = 223.240 Ep = 1519.761489 Es = 5621.984942

Pfan = 835.000 E1 = 7141.746 E2 = 7961.091 A = 192.785663

Iteration 1									
....									
Node: 1	2	3	4	5	6				
V: 12.97	9.082	10.616	2.529	12.13	11.444				
L: 24.38	23.77	7.31	1.52	20.42	11.89				
Q: 0.710	0.24	0.94	0.94	0.94	1.88				
DPz: 0.00	0	0	25	0	55				
Dz: 0.000	0	0	0	0	0				
C: 0.230	1.68	0.24	0.52	1.06	0.24				
Df: 0.284	0.183	0.336	0.61	0.314	0.467				
Dv: 0.267	0.187	0.335	0.688	0.309	0.451				
f: 0.021	0.024	0.02	0.02	0.021	0.019				
DP: 223.3	232.103	46.286	27.191	211.801	112.297				
mu: 0.58	0.86	0.23	0.393	0.764	0.333				
Ks: 19.08	13.033	5.314	0	18.825	12.287				
Kt: 19.08	13.033	40.908	0	18.825	79.405				
T: 1.000	1	0.183	0	1	0.211				
DPmax: 0.0	0	0	27.191	27.191	82.191				
Pup: 209.7	209.766	256.609	27.191	256.609	373.033				
Pdn: 0.00	0	209.766	0	27.191	256.609				
DPt: 209.7	209.766	46.843	27.191	229.419	116.423				
DPr: 209.7	209.766	46.843	0.1	229.419	61.423				
ch1: 0	0	1	0	4	3				
ch2: 0	0	2	0	0	5				
DPp: 381.6	390.686	158.683	361.288	324.098	112.297				
DPex: -8.8	-17.654	0	21.744	0	0				
D: 0.267	0.187	0.335	0	0.309	0.461				
H: 0.000	0	0	0.61	0	0				
W: 0.000	0	0	0.609	0	0				
DPexmax = 56.058 Ep = 1519.761480 Es = 5608.712457									
Pfan = 835.000 E1 = 7128.474 E2 = 7570.991 A = 181.391768									
....									

Node: 7	8	9	10	11	12	13	14	15	16
V: 3.832	3.832	8.408	8.478	9.928	11.539	15.126	12.795	10.61	11.923
L: 4.270	1.22	7.62	13.72	9.16	6.71	10.67	4.57	9.75	6.1
Q: 0.280	0.28	0.56	0.56	0.47	0.47	0.94	1.51	0.19	0.19
DPz: 25.00	37.5	0	0	0	0	0	0	0	0
Dz: 0.30	0.305	0	0	0	0	0	0	0	0
C: 1.040	5.3	1.26	2.19	1.78	1.19	0.12	0.04	1.27	1.09
Df: 0.30	0.306	0.258	0.257	0.215	0.197	0.249	0.328	0.133	0.124
Dv: 0.30	0.306	0.292	0.29	0.243	0.224	0.284	0.389	0.154	0.144
f: 0.023	0.023	0.022	0.022	0.023	0.023	0.022	0.02	0.026	0.026
DP: 36.9	85.012	81.197	145.459	163.01	158.41	143.306	31.689	213.529	202.027
mu: 0.41	1.644	0.568	0.979	0.677	0.462	0.294	0.125	0.478	0.337
Ks: 0.000	0	6.067	12.224	7.153	4.902	9.194	4.197	4.923	2.9
Kt: 0.000	0	6.067	20.809	7.153	4.902	24.372	52.764	4.923	2.9
T: 0.000	0	1	0.642	1	1	0.444	0.121	1	1
DPmax: 36.	85.012	85.012	85.012	0	0	0	85.012	0	0
Pup: 85.01	85.012	165.629	310.156	172.506	172.506	310.156	341.233	193.666	193.666
Pdn: 48.0	0	85.012	165.629	0	0	172.506	310.156	0	0
DPt: 36.9	85.012	80.617	144.527	172.506	172.506	137.651	31.076	193.666	193.666
DPr: 36.9	0.1	80.617	144.527	172.506	172.506	137.651	31.076	193.666	193.666
ch1: 0	0	7	9	0	0	11	10	0	0
ch2: 0	0	8	0	0	0	12	13	0	0
DPp: 434.3	482.379	397.367	316.17	477.026	472.426	314.016	170.711	518.025	506.523
DPex: 27.6	-20.411	0	0	-15.059	-10.458	0	0	-56.058	-44.556
D: 0.306	0.305	0	0	0	0	0	0	0	0
H: 0.000	0	0.254	0.254	0.254	0.254	0.254	0.254	0.152	0.152
W: 0.000	0	0.262	0.26	0.186	0.16	0.245	0.465	0.118	0.105
DPexmax = 56.058 Ep = 1519.761480 Es = 5608.712457									
Pfan = 835.000 E1 = 7128.474 E2 = 7570.991 A = 181.391768									

Iteration 1									
Node: 17	18	19							
V: 12.97	5.231	4.737							
L: 9.140	7.01	3.66							
Q: 0.380	1.88	1.88							
DPz: 0.00	10	12.5							
Dz: 0.000	0	0							
C: 0.340	4.28	3.06							
Df: 0.16	0.599	0.63							
Dv: 0.19	0.698	0.74							
f: 0.024	0.019	0.019							
DP: 166.4	83.872	55.15							
mu: 0.31	3.044	2.253							
Ks: 5.64	12.723	6.257							
Kt: 15.43	88.868	100.677							
T: 0.432	0.198	0.099							
DPmax: 0.0	95.012	107.512							
Pup: 341.2	414.465	461.967							
Pdn: 193.6	341.233	414.465							
DPt: 147.5	73.232	47.503							
DPr: 147.5	63.232	35.003							
ch1: 15	14	18							
ch2: 16	17	0							
DPp: 304.4	139.022	55.15							
DPex: 0.00	0	0							
D: 0.000	0	0							
H: 0.203	0.61	0.61							
W: 0.14	0.589	0.651							
DPexmax = 56.058 Ep = 1519.761480 Es = 5608.712457									
Pfan = 835.000 E1 = 7128.474 E2 = 7570.991 A = 181.391768									

Iteration 2

Node: 1	2	3	4	5	6
V: 12.66	8.72	10.664	2.529	12.52	11.764
L: 24.380	23.77	7.31	1.52	20.42	11.89
Q: 0.710	0.24	0.94	0.94	0.94	1.88
DPz: 0.00	0	0	25	0	55
Dz: 0.000	0	0	0	0	0
C: 0.230	1.58	0.24	0.52	1.06	0.24
Df: 0.267	0.187	0.335	0.61	0.309	0.461
Dv: 0.267	0.187	0.335	0.688	0.309	0.461
f: 0.021	0.024	0.02	0.02	0.021	0.019
DP: 209.5	210.765	46.782	27.191	227.95	116.181
mu: 0.58	0.865	0.23	0.393	0.749	0.332
Ks: 19.08	13.047	5.314	0	18.804	12.279
Kt: 19.08	13.047	40.92	0	18.804	79.385
T: 1.000	1	0.182	0	1	0.211
DPmax: 0.0	0	0	27.191	27.191	82.191
Pup: 209.6	209.611	256.4	27.191	256.4	372.741
Pdn: 0.00	0	209.611	0	27.191	256.4
DPt: 209.6	209.611	46.788	27.191	229.209	116.342
DPr: 209.6	209.611	46.788	0.1	229.209	61.342
ch1: 0	0	1	0	4	3
ch2: 0	0	2	0	0	5
DPp: 372.5	373.728	162.963	371.321	344.131	116.181
DPex: 0.2	-0.986	0	1.42	0	0
D: 0.267	0.187	0.335	0	0.309	0.461
H: 0.000	0	0	0.61	0	0
W: 0.000	0	0	0.609	0	0

DPexmax = 44.728 Ep = 1519.761489 Es = 5614.032027

Pfan = 835.000 E1 = 7133.794 E2 = 7609.243 A = 182.538406

Node: 7	8	9	10	11	12	13	14	15	16
V: 3.832	3.832	8.385	8.457	10.156	11.941	14.887	12.697	10.205	11.725
L: 4.270	1.22	7.62	13.72	9.16	6.71	10.67	4.57	9.75	6.1
Q: 0.280	0.28	0.56	0.56	0.47	0.47	0.94	1.51	0.19	0.19
DPz: 25.00	37.5	0	0	0	0	0	0	0	0
Dz: 0.30	0.305	0	0	0	0	0	0	0	0
C: 1.040	5.3	1.26	2.19	1.78	1.19	0.12	0.04	1.27	1.09
Df: 0.30	0.305	0.258	0.257	0.212	0.192	0.261	0.329	0.136	0.125
Dv: 0.30	0.305	0.292	0.291	0.243	0.224	0.284	0.389	0.154	0.144
f: 0.023	0.023	0.022	0.022	0.023	0.023	0.022	0.02	0.026	0.026
DP: 36.9	85.012	80.712	144.682	171.522	171.31	137.652	31.125	194.648	194.163
mu: 0.41	1.644	0.558	0.979	0.673	0.448	0.294	0.125	0.48	0.338
Ks: 0.000	0	6.069	12.226	7.157	4.914	9.193	4.203	4.917	2.897
Kt: 0.000	0	6.069	20.812	7.157	4.914	24.389	52.794	4.917	2.897
T: 0.000	0	1	0.642	1	1	0.443	0.121	1	1
DPmax: 36.	85.012	85.012	85.012	0	0	0	85.012	0	0
Pup: 85.01	85.012	165.553	309.94	172.486	172.486	309.94	341.01	193.724	193.724
Pdn: 48.02	0	85.012	165.553	0	0	172.486	309.94	0	0
DPt: 36.9	85.012	80.541	144.387	172.486	172.486	137.454	31.07	193.724	193.724
DPr: 36.9	85.012	80.541	144.387	172.486	172.486	137.454	31.07	193.724	193.724
ch1: 0	0	7	9	0	0	11	10	0	0
ch2: 0	0	8	0	0	0	12	13	0	0
DPp: 417.5	465.552	380.54	299.828	464.319	464.108	292.798	155.146	466.086	465.601
DPex: 44.7	-3.294	0	0	-2.061	-1.849	0	0	-3.827	-3.342
D: 0.305	0.305	0	0	0	0	0	0	0	0
H: 0.000	0	0.254	0.254	0.254	0.254	0.254	0.254	0.152	0.152
W: 0.000	0	0.263	0.261	0.182	0.155	0.249	0.468	0.122	0.107

DPexmax = 44.728 Ep = 1519.761489 Es = 5614.032027

Pfan = 835.000 E1 = 7133.794 E2 = 7609.243 A = 182.538406

Iteration 2

Node: 17	18	19
V: 12.39	4.917	4.377
L: 9.140	7.01	3.66
Q: 0.380	1.88	1.88
DPz: 0.00	10	12.5
Dz: 0.000	0	0
C: 0.340	4.28	3.06
Df: 0.173	0.618	0.654
Dv: 0.19	0.701	0.744
f: 0.024	0.019	0.019
DP: 147.4	75.145	48.876
mu: 0.31	3.135	2.341
Ks: 5.62	12.797	6.318
Kt: 15.40	88.964	100.872
T: 0.432	0.199	0.099
DPmax: 0.0	95.012	107.512
Pup: 341.0	414.5	462.259
Pdn: 193.7	341.01	414.5
DPt: 147.2	73.491	47.758
DPr: 147.2	63.491	35.258
ch1: 15	14	18
ch2: 16	17	0
DPp: 271.4	124.021	48.876
DPex: 0.00	0	0
D: 0.000	0	0
H: 0.203	0.61	0.61
W: 0.15	0.627	0.704

DPexmax = 44.728 Ep = 1519.761489 Es = 5614.032027

Pfan = 835.000 E1 = 7133.794 E2 = 7609.243 A = 182.538406

	Iteration 3								
Node: 1	2	3	4	5	6				
V: 12.64	8.696	10.66	2.529	12.646	11.772				
L: 24.38	23.77	7.31	1.52	20.42	11.89				
Q: 0.710	0.24	0.94	0.94	0.94	1.88				
DPz: 0.00	0	0	25	0	55				
Dz: 0.00	0	0	0	0	0				
C: 0.230	1.58	0.24	0.62	1.06	0.24				
Df: 0.267	0.187	0.336	0.61	0.309	0.461				
Dv: 0.267	0.187	0.336	0.688	0.309	0.461				
f: 0.021	0.024	0.02	0.02	0.021	0.019				
DP: 209.4	209.428	46.746	27.191	229.003	116.286				
mu: 0.58	0.865	0.23	0.393	0.749	0.332				
Ks: 19.0	13.048	5.314	0	18.802	12.279				
Kt: 19.0	13.048	40.921	0	18.802	79.384				
T: 1.000	1	0.182	0	1	0.211				
DPmax: 0.0	0	0	27.191	27.191	82.191				
Pup: 209.5	209.673	256.362	27.191	256.362	372.68				
Pdn: 0.00	0	209.673	0	27.191	256.362				
DPt: 209.5	209.573	46.779	27.191	229.161	116.328				
DPr: 209.5	209.573	46.779	0.1	229.161	61.328				
ch1: 0	0	1	0	4	3				
ch2: 0	0	2	0	0	5				
DPp: 372.4	372.46	163.032	372.479	345.288	116.286				
DPex: 0.2	0.219	0	0.201	0	0				
D: 0.267	0.187	0.336	0	0.309	0.461				
H: 0.000	0	0	0.61	0	0				
W: 0.00	0	0	0.609	0	0				
DPexmax = 47.896 Ep = 1519.761480 Es = 5615.419680									
Pfan = 836.000 E1 = 7136.181 E2 = 7615.640 A = 182.730160									
Node: 7	8	9	10	11	12	13	14	15	16
V: 3.83	3.832	8.378	8.46	10.183	11.978	14.879	12.688	10.186	11.714
L: 4.270	1.22	7.62	13.72	9.16	6.71	10.67	4.57	9.75	6.1
Q: 0.280	0.28	0.56	0.56	0.47	0.47	0.94	1.61	0.19	0.19
DPz: 25.0	37.5	0	0	0	0	0	0	0	0
Dz: 0.30	0.305	0	0	0	0	0	0	0	0
C: 1.040	5.3	1.26	2.19	1.78	1.19	0.12	0.04	1.27	1.09
Df: 0.30	0.305	0.259	0.257	0.212	0.192	0.251	0.329	0.136	0.125
Dv: 0.30	0.305	0.292	0.291	0.242	0.224	0.284	0.389	0.154	0.144
f: 0.023	0.023	0.022	0.022	0.023	0.023	0.022	0.02	0.026	0.026
DP: 36.9	85.012	80.564	144.41	172.529	172.529	137.472	31.076	193.76	193.76
mu: 0.41	1.644	0.568	0.98	0.672	0.448	0.294	0.125	0.48	0.338
Ks: 0.000	0	6.069	12.227	7.168	4.916	9.193	4.203	4.917	2.897
Kt: 0.000	0	6.069	20.813	7.168	4.916	24.391	52.798	4.917	2.697
T: 0.000	0	1	0.642	1	1	0.443	0.121	1	1
DPmax: 36.	85.012	85.012	85.012	0	0	0	85.012	0	0
Pup: 85.0	85.012	165.64	309.902	172.474	172.474	309.902	340.968	193.698	193.698
Pdn: 48.0	0	85.012	165.64	0	0	172.474	309.902	0	0
DPt: 36.9	85.012	80.527	144.362	172.474	172.474	137.428	31.066	193.698	193.698
DPr: 36.9	0.1	80.527	144.362	172.474	172.474	137.428	31.066	193.698	193.698
ch1: 0	0	7	9	0	0	11	10	0	0
ch2: 0	0	8	0	0	0	12	13	0	0
DPp: 414.4	462.447	377.434	296.881	462.471	462.471	289.942	152.471	462.472	462.472
DPex: 47.8	-0.126	0	0	-0.151	-0.151	0	0	-0.152	-0.152
D: 0.305	0.305	0	0	0	0	0	0	0	0
H: 0.000	0	0.254	0.254	0.254	0.254	0.254	0.254	0.152	0.152
W: 0.000	0	0.263	0.261	0.182	0.154	0.249	0.469	0.123	0.107
DPexmax = 47.896 Ep = 1519.761480 Es = 5615.419680									
Pfan = 836.000 E1 = 7136.181 E2 = 7615.640 A = 182.730160									

Iteration 3									
Node: 17	18	19							
V: 12.38	4.857	4.314							
L: 9.140	7.01	3.66							
Q: 0.380	1.88	1.88							
DPz: 0.00	10	12.5							
Dz: 0.000	0	0							
C: 0.340	4.28	3.06							
Df: 0.17	0.622	0.658							
Dv: 0.19	0.702	0.745							
f: 0.024	0.019	0.019							
DP: 147.3	73.571	47.824							
mu: 0.31	3.153	2.357							
Ks: 5.6	12.813	6.33							
Kt: 15.40	88.99	100.918							
T: 0.432	0.199	0.1							
DPmax: 0.0	95.012	107.512							
Pup: 340.9	414.512	462.32							
Pdn: 193.6	340.968	414.512							
DPt: 147.2	73.544	47.809							
DPr: 147.2	63.544	35.309							
ch1: 15	14	18							
ch2: 16	17	0							
DPp: 268.7	121.395	47.824							
DPex: 0.00	0	0							
D: 0.000	0	0							
H: 0.203	0.61	0.61							
W: 0.15	0.634	0.714							
DPexmax = 47.896 Ep = 1519.761480 Es = 5615.419680									
Pfan = 836.000 E1 = 7136.181 E2 = 7615.640 A = 182.730160									

ASHRAE Example Problem (T-Method)

Iteration 777									
Node: 1	2	3	4	5	6				
V: 12.64	8.696	10.66	2.529	12.546	11.772				
L: 24.38	23.77	7.31	1.52	20.42	11.89				
Q: 0.710	0.24	0.94	0.94	0.94	1.88				
DPz: 0.00	0	0	25	0	55				
Dz: 0.000	0	0	0	0	0				
C: 0.230	1.58	0.24	0.62	1.06	0.24				
Df: 0.287	0.187	0.335	0.61	0.309	0.461				
Dv: 0.287	0.187	0.335	0.688	0.309	0.461				
f: 0.021	0.024	0.02	0.02	0.021	0.019				
DP: 209.4	209.427	46.746	27.191	229.001	116.286				
mu: 0.58	0.865	0.23	0.393	0.749	0.332				
Ks: 19.08	13.048	5.314	0	18.802	12.279				
Kt: 19.08	13.048	40.921	0	18.802	79.384				
T: 1.000	1	0.182	0	1	0.211				
DPmax: 0.0	0	0	27.191	27.191	82.191				
Pup: 209.5	209.573	256.352	27.191	256.352	372.68				
Pdn: 0.00	0	209.573	0	27.191	256.352				
DPt: 209.5	209.573	46.779	27.191	229.161	116.328				
DPr: 209.5	209.573	46.779	0.1	229.161	61.328				
ch1: 0	0	1	0	4	3				
ch2: 0	0	2	0	0	5				
DPp: 372.4	372.46	163.032	372.479	345.288	116.286				
DPex: 0.2	0.219	0	0.201	0	0				
D: 0.279	0.203	0.33	0	0.305	0.457				
H: 0.000	0	0	0.61	0	0				
W: 0.000	0	0	0.61	0	0				
DPexmax = 47.896 Ep = 1519.761489 Es = 5615.419680									
Pfan = 836.000 E1 = 7136.181 E2 = 7710.788 A = 186.582344									

Node: 7	8	9	10	11	12	13	14	15	16
V: 3.832	3.832	8.378	8.46	10.183	11.978	14.879	12.688	10.185	11.714
L: 4.270	1.22	7.62	13.72	9.16	6.71	10.67	4.57	9.75	6.1
Q: 0.280	0.28	0.56	0.56	0.47	0.47	0.94	1.51	0.19	0.19
DPz: 26.00	37.5	0	0	0	0	0	0	0	0
Dz: 0.30	0.305	0	0	0	0	0	0	0	0
C: 1.040	5.3	1.26	2.19	1.78	1.19	0.12	0.04	1.27	1.09
Df: 0.30	0.305	0.259	0.257	0.212	0.192	0.251	0.329	0.136	0.125
Dv: 0.30	0.305	0.292	0.291	0.242	0.224	0.284	0.389	0.154	0.144
f: 0.023	0.023	0.022	0.022	0.023	0.023	0.022	0.02	0.026	0.026
DP: 36.9	85.012	80.553	144.408	172.529	172.529	137.471	31.076	193.759	193.759
mu: 0.41	1.644	0.558	0.98	0.672	0.448	0.294	0.125	0.48	0.338
Ks: 0.000	0	6.069	12.227	7.158	4.916	9.193	4.203	4.917	2.897
Kt: 0.000	0	6.069	20.813	7.158	4.916	24.391	52.798	4.917	2.897
T: 0.000	0	1	0.642	1	1	0.443	0.121	1	1
DPmax: 36.	85.012	85.012	85.012	0	0	0	85.012	0	0
Pup: 86.01	85.012	165.54	309.902	172.474	172.474	309.902	340.968	193.698	193.698
Pdn: 48.02	0	85.012	165.54	0	0	172.474	309.902	0	0
DPt: 36.9	85.012	80.527	144.362	172.474	172.474	137.428	31.066	193.698	193.698
DPr: 36.9	0.1	80.527	144.362	172.474	172.474	137.428	31.066	193.698	193.698
ch1: 0	0	7	9	0	0	11	10	0	0
ch2: 0	0	8	0	0	0	12	13	0	0
DPp: 414.4	462.447	377.434	298.881	462.471	462.471	289.942	152.471	462.472	462.472
DPex: 47.8	-0.126	0	0	-0.151	-0.151	0	0	-0.152	-0.152
D: 0.306	0.305	0	0	0	0	0	0	0	0
H: 0.000	0	0.254	0.254	0.254	0.254	0.254	0.254	0.152	0.152
W: 0.000	0	0.279	0.254	0.178	0.152	0.254	0.483	0.127	0.127
DPexmax = 47.896 Ep = 1519.761489 Es = 5615.419680									
Pfan = 836.000 E1 = 7136.181 E2 = 7710.788 A = 186.582344									
Iteration 777									
Node: 17	18	19							
V: 12.38	4.857	4.314							
L: 9.140	7.01	3.66							
Q: 0.380	1.88	1.88							
DPz: 0.00	10	12.5							
Dz: 0.000	0	0							
C: 0.340	4.28	3.06							
Df: 0.173	0.622	0.658							
Dv: 0.19	0.702	0.745							
f: 0.024	0.019	0.019							
DP: 147.3	73.565	47.821							
mu: 0.31	3.153	2.357							
Ks: 5.62	12.813	6.33							
Kt: 15.40	88.99	100.918							
T: 0.432	0.199	0.1							
DPmax: 0.0	95.012	107.512							
Pup: 340.9	414.512	462.32							
Pdn: 193.6	340.968	414.512							
DPt: 147.2	73.544	47.809							
DPr: 147.2	63.544	35.309							
ch1: 15	14	18							
ch2: 16	17	0							
DPp: 268.7	121.395	47.824							
DPex: 0.00	0	0							
D: 0.000	0	0							
H: 0.203	0.61	0.61							
W: 0.152	0.66	0.711							
DPexmax = 47.896 Ep = 1519.761489 Es = 5615.419680									
Pfan = 835.000 E1 = 7136.181 E2 = 7710.788 A = 186.582344									

APPENDIX E

FIVE DUCT SECTION PROBLEM COMPUTER OUTPUT

T-METHOD

Five Duct Section Problem (T-Method)

	Iteration 0					
Node	1	2	3	4	5	
V	7.5	7.5	10.756	7.5	7.5	
L	14	12	8	16	19.81	
Q	0.7	0.22	0.92	0.5	1.42	
DPz	25	37.5	0	0	37.5	
Dz	0	0	0.33	0	0	
C	0.8	0.65	0.18	0.65	1.5	
Df	0.3	0.193	0.33	0.291	0.491	
Dv	0.278	0.161	0.33	0.22	0.442	
f	0.019	0.019	0.019	0.019	0.019	
DP	81.888	99.268	44.472	57.165	114.006	
mu	0.581	0.354	0.211	0.493	1.113	
Ks	12.497	5.319	0	10.528	23.285	
Kt	12.497	5.319	17.816	10.528	50.258	
T	1	1	0	1	0.459	
DPmax	25	37.5	81.972	0	119.472	
Pup	190.411	190.411	234.883	234.883	402.185	
Pdn	0	0	190.411	0	234.883	
DPt	190.411	190.411	44.472	234.883	167.303	
DPr	165.411	152.911	44.472	234.883	129.803	
ch1	0	0	1	0	3	
ch2	0	0	2	0	4	
DPp	240.366	257.746	158.478	171.172	114.006	
DPex	161.819	144.439	0	231.013	0	
D	0	0.161	0.33	0.22	0.442	
H	0.254	0	0	0	0	
W	0.367	0	0	0	0	
DPexmax = 231.013 Ep = 732.006514 Es = 2414.636029						
Pfan = 402.185 E1 = 3146.643 E2 = 3774.112 A = 70.306196						
....						
	Iteration 1					
....						
Node	1	2	3	4	5	
V	11.498	10.776	10.756	13.197	9.265	
L	14	12	8	16	19.81	
Q	0.7	0.22	0.92	0.5	1.42	
DPz	25	37.5	0	0	37.5	
Dz	0	0	0.33	0	0	
C	0.8	0.65	0.18	0.65	1.5	
Df	0.247	0.161	0.33	0.22	0.442	
Dv	0.278	0.165	0.33	0.22	0.437	
f	0.022	0.025	0.02	0.022	0.019	
DP	187.306	209.881	46.98	238.642	159.175	
mu	0.57	0.399	0.223	0.502	1.044	
Ks	12.245	5.449	0	10.563	22.989	
Kt	12.245	5.449	17.694	10.563	58.813	
T	1	1	0	1	0.457	
DPmax	25	37.5	84.48	0	121.98	
Pup	190.018	190.018	236.999	236.999	402.925	
Pdn	0	0	190.018	0	236.999	
DPt	190.018	190.018	46.98	236.999	165.926	
DPr	165.018	152.518	46.98	236.999	128.426	
ch1	0	0	1	0	3	
ch2	0	0	2	0	4	
DPp	393.461	416.037	206.155	397.817	159.175	
DPex	9.464	-13.112	0	5.107	0	
D	0	0.165	0.33	0.22	0.437	
H	0.254	0	0	0	0	
W	0.24	0	0	0	0	
DPexmax = 13.112 Ep = 733.352712 Es = 2386.633314						
Pfan = 402.925 E1 = 3128.986 E2 = 3615.319 A = 66.604270						
....						
	Iteration 2					
....						
Node	1	2	3	4	5	
V	11.576	10.258	10.756	13.157	9.464	
L	14	12	8	16	19.81	
Q	0.7	0.22	0.92	0.5	1.42	
DPz	25	37.5	0	0	37.5	
Dz	0	0	0.33	0	0	
C	0.8	0.65	0.18	0.65	1.5	
Df	0.246	0.165	0.33	0.22	0.437	
Dv	0.277	0.165	0.33	0.22	0.437	
f	0.022	0.024	0.02	0.022	0.019	
DP	189.911	190.564	46.98	236.899	165.03	
mu	0.569	0.401	0.223	0.502	1.037	
Ks	12.244	5.454	0	10.563	22.96	
Kt	12.244	5.454	17.697	10.563	58.784	
T	1	1	0	1	0.457	
DPmax	25	37.5	84.48	0	121.98	
Pup	190.037	190.037	237.017	237.017	402.808	
Pdn	0	0	190.037	0	237.017	
DPt	190.037	190.037	46.98	237.017	165.791	
DPr	165.037	152.537	46.98	237.017	128.291	
ch1	0	0	1	0	3	
ch2	0	0	2	0	4	
DPp	401.921	402.574	212.01	401.928	165.03	
DPex	0.887	0.235	0	0.88	0	
D	0	0.165	0.33	0.22	0.437	
H	0.254	0	0	0	0	
W	0.238	0	0	0	0	
DPexmax = 0.887 Ep = 733.141026 Es = 2394.581517						
Pfan = 402.808 E1 = 3127.723 E2 = 3612.158 A = 66.536100						

Five Duct Section Problem (T-Method)

Iteration 777

……

Node	1	2	3	4	5
V	11.581	10.241	10.758	13.158	9.484
L	14	12	8	16	19.81
Q	0.7	0.22	0.92	0.5	1.42
DPz	25	37.5	0	0	37.5
Dz	0	0	0.33	0	0
C	0.8	0.65	0.18	0.65	1.5
Df	0.246	0.165	0.33	0.22	0.437
Dv	0.277	0.165	0.33	0.22	0.437
f	0.022	0.024	0.02	0.022	0.019
DP	190.079	189.953	46.98	236.854	165.822
mu	0.569	0.401	0.223	0.502	1.036
Ks	12.243	5.454	0	10.563	22.957
Kt	12.244	5.464	17.897	10.563	58.764
T	1	1	0	1	0.457
DPmax	25	37.5	64.48	0	121.98
Pup	190.037	190.037	237.017	237.017	402.808
Pdn	0	0	190.037	0	237.017
DPt	190.037	190.037	46.98	237.017	165.791
DPr	165.037	152.537	46.98	237.017	128.291
ch1	0	0	1	0	3
ch2	0	0	2	0	4
DPp	401.921	402.574	212.01	401.928	165.03
DPex	0.887	0.235	0	0.88	0
D	0	0.178	0.33	0.229	0.432
H	0.254	0	0	0	0
W	0.254	0	0	0	0

DPexmax = 0.887 Ep = 733.141026 Es = 2394.581517

Pfan = 402.808 E1 = 3127.723 E2 = 3657.738 A = 67.589473

……

Calculation completed

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VITA

Fan Wang

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Master of Science

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