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# NUMERICAL EXPRESSIONS FOR VENTILATION PARAMETERS

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## ABSTRACT

The computer-aided ventilation system design requires the programming of a large number of empirical tables and observations on the use of mathematical expressions which describe numerous ventilation parameters. In order to use computers with efficiency and to reduce programming inessentials, a set of numerical approximations are developed. These expressions are divided into two categories: 1) external variables and 2) system variables. The external variables are the psychrometrics, altitude and temperature corrections. The system variables are basically the duct resistance calculations. Programming details are also discussed and methods to unite a program which allow the flow of logic from one branch to another with minimal repetition of calculations.

## INTRODUCTION

The availability of a microcomputer opens the possibility for computer-aided ventilation design and optimization of designed systems by considering several feasible solutions. In order to achieve this it is necessary to download a large number of tables and perform a large number of calculations based on the values obtained from these tables. This aspect is a limitation, especially for generally slow microcomputers and interpretive languages. In order to use computers with efficiency and to reduce programming inessentials such as tables, it is important to investigate the possibilities of developing a set of numerical approximations to obtain these values. Although this process can be used to generate the tables as needed, thus economizing memory, one must be careful in the organization of the programming steps so that the numerical approximations are used with economy, and thus calculation efficiency is also preserved. Once the tables are downloaded, looking up a value is, in general, faster than its calculation.

If one separates the conditions which are changed during the design process into two categories: 1) external variables and 2) system variables, then it would be possible to develop a computational strategy to minimize the number of calculations performed. In this paper a number of numerical approximations are provided to achieve this aim. The computational strategy presented has not been checked for its optimality. This was simply due to the heuristic approach taken to obtain a reasonably efficient programming strategy without much attention paid to elegance of the computational scheme. It might very well turn out to be optimal for a number of computer programming languages, but such consideration would be beyond the scope of this paper.

NUMERICAL APPROXIMATIONS FOR EXTERNAL VARIABLES

The external variables of a ventilation design are the psychrometric parameters which lead to vapor, altitude and temperature corrections for industrial ventilation design as well as heating/air conditioning calculations. The specifications of the conditions which generate these variables are normally made in terms of system temperature ($^{o}C$), relative humidity (R) and barometric pressure (Pb). Usually the normal barometric pressure is not specified, but the altitude of the location of the installation is known. This altitude (A) may be related to standard sea level barometric pressure of 760 mm Hg by

$$Pb = 760 - 0.0926\ A \qquad \text{mmHg} \qquad (1)$$

In order to define the psychrometric variables, it is necessary to estimate the vapor pressure of water, Pw, which may be given within ± 3 percent accuracy between -15$^{o}$C and 150$^{o}$C by:

$$Pw = \exp(21.1 - \frac{5346.765}{T - 273.2} - 1.398 \times 10^{-5}\ T^{2}) \qquad \text{mm Hg} \qquad (2)$$

If the relative humidity is expressed as a fraction rather than the usual percentage, and with the system temperature expressed as $^{o}C$, Equation (2) may be used to calculate the density of moist air ($\rho$) and the moisture content (W) approximately:

$$\rho = \frac{Pb - 0.3786\ R\ Pw}{0.587 + 2.15 \times 10^{-3}\ T} \qquad g/m^{3} \qquad (3)$$

and

$$W = 0.622\ \frac{R\ Pw}{Pb - R\ .\ Pw} \qquad \text{g/g of dry air} \qquad (4)$$

These estimates are also within 3 percent of the reported values (ref. 1) for the temperaure range of -15$^{o}$C to 75$^{o}$C. Similarly, within the same accuracy and for the same temperature range, the heat content may be approximated by:

$$H = 18 + 1.013\,T + W(2500 + 1.88\,T) \qquad \text{Joules/g} \qquad (5)$$

The equations above may be used to generate values which describe the external conditions under which a ventilation system must work. However, for heating and air-conditioning design calculations, the heat and moisture input rates depend upon specified conditions and air-flow rate, and these variables may be combined to express these rates:

$$\Delta W^1 = \frac{60}{1000}\, Q \cdot \rho_1 (W_2 - W_1) \qquad \text{kg/min} \qquad (6)$$

$$\Delta H^1 = \frac{60}{1000}\, Q \cdot \rho_1 (H_2 - H_1) \qquad \text{Kjoules/min} \qquad (7)$$

NUMERICAL APPROXIMATION FOR SYSTEM VARIABLES

The system variables include the calculation of velocity pressures and pressure losses through a ductwork and attendant entry, elbow and junction losses for specified flow rates and duct sizes. In the interest of space the estimations will be limited to round ductwork, since the extension to oblong duct cross section is simple. The velocity pressure estimated directly from the Bernoulli's equation:

$$h_v = \rho\left(\frac{142}{v}\right)^2 = 1.244 \times 10^{-4}\,\frac{\rho D^4}{Q^2} \qquad \text{mmH}_2\text{O} \qquad (8)$$

$$h_L - \frac{4.032\, L\, h_v}{D^{1.23}} = \frac{5.02 \times 10^{-4}\, D^{2.77}\, L\, \rho}{Q^2} \qquad \text{mm H}_2\text{O} \qquad (9)$$

The estimation of pressure losses through elbows with turning radii x present an important problem. There is no theoretical analysis of these losses and the empirical values provided in several sources conflict. The elbow losses given as fraction of velocity held in the most widely used manual "Industrial Ventilation" (ref. 2) are based on an estimate given in a text first published in 1939 (ref. 3) and conflicts with the pressure losses calculated on the basis of pressure drop through an equivalent length of straight duct. Either estimate is also in conflict with two other widely used texts (refs. 4 and 5). In view of these uncertainties and due to lack of more recent data, the approximation given below is based on the pressure losses calculated on the basis of pressure drop through an equivalent length of straight duct as reported in the "Industrial Ventilation" manual (ref. 2). For an elbow with turning radius X, the elbow losses may be estimated by:

$$h_{L_e} = \frac{0.876\ h_v}{D^{0.05}\ X^{1.18}} = \frac{1.09 \times 10^{-4}\ D^{3.95}\ \rho}{Q^2\ X^{1.18}} \qquad \text{mm } H_2O \qquad (10)$$

The losses at a junction may be similarly estimated from the data given in "Industrial Ventilation" (ref. 2). For a junction with an angle between the main and the branch, if the static pressure regain is ignored, the estimate becomes:

$$h_{L_j} = \sin\theta(.35 + .65 \sin^8 \theta)\ h_v(\text{branch}) \qquad \text{mm } H_2O \qquad (11)$$

or with the diameter and the flow of the entering branch $D_b$ and $Q_b$ respectively:

$$h_{L_j} = 1.244 \times 10^{-4} \sin\theta(.35 + .65 \sin^8 \theta)\ \frac{\rho\ D_b^4}{Q_b^2} \qquad \text{mm } H_2O \qquad (12)$$

Equations 8-12 provide a basis for the calculation of system pressure and flow values for any given point in the system.

## CALCULATION PROCEDURES

Calculation of psychrometric variables presents a simple hierarchial procedure in which only the variables influenced by the input values are calculated. The calculation flow chart is given in Figure 1. With slight modification the first four blocks of this flow chart may be used at the beginning of industrial ventilation system design to obtain temperature and altitude corrections for ventilation design. The calculated parameters are entered as user defined functions in the beginning of the program and thus afford considerable economy of program space. The initial values for the input variables can be any appropriate number. In this way, most frequently used values can serve as default parameters. After the first cycle, input default can be set to the previous value of the input so that minimal key in would be required.

Calculation of ventilation system design values requires substantially more sophisticated programming. However, several simple organizational features would not only simplify the programming tasks, but also enhance the calculation efficiency. The first consideration in this respect is to organize the design in a hierarchy of sub-branches, branches, and a main trunk. The ordering of branches is accomplished by numbering the branches consecutively from physically most distant to the fan entry to the nearest with respect to the entry into the main. Similarly, the sub-branches are ordered as a two dimensional array with respect to the branch they belong to

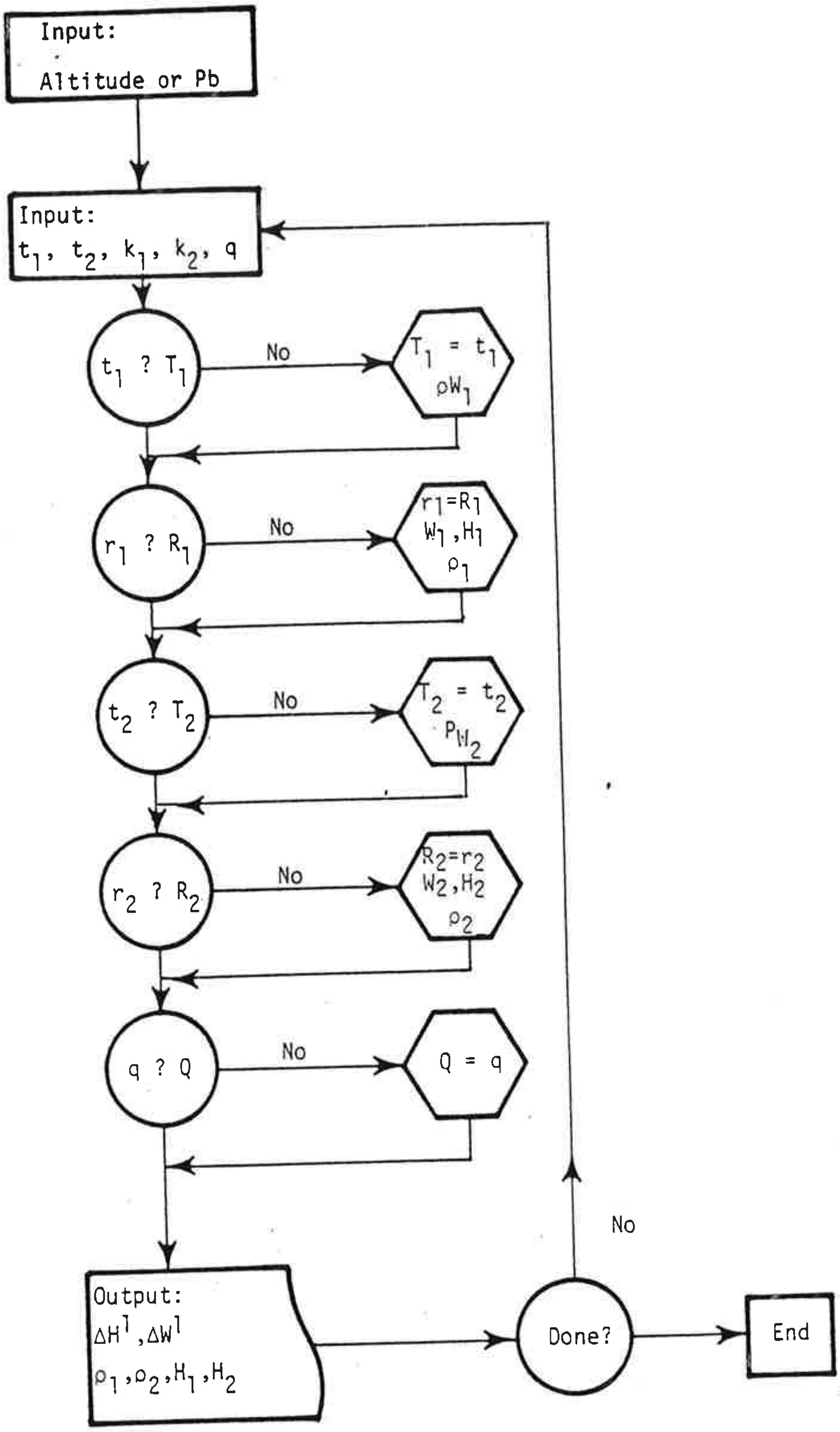


Figure 1. Flow chart for psychrometric calculations

and their order of entry to the branch with respect to the end of the branch. This process can be carried out in the same manner for any number of sub-divisions increasing the dimension of the array by one. This ordering procedure results in one dimensional arrays for main, two dimensional arrays for branches and three or more dimensional arrays for sub-branches. Each terminal sub-branch or branch is specified by a nominal flow rate, coefficient of entry expressed as a multiplier for velocity pressure, additional losses (flexible duct, traps, etc.), and number of elbows present. In general, the turning radii of elbows may be set to be a nominal value of 2.5 as standard practice, but provisions should be made for deviating from this default value. The transport velocity range can be preset for branches, sub-branches and main, again with a provision to change the default values.

The calculations proceed in the order of highest dimension to lowest dimension and lowest order to the highest order within the dimension. At the end of each dimensional category the static pressure and total flow for that block is stored. At each junction a comparative criteria should be provided for the computer to decide whether to redesign the previous points leading to that junction or adjust the flow of all previous connections to the static pressure of the junction. Usually, if the static pressure of the two legs of the junction are such that

$$\left|\left|\frac{hs_1}{hs_2} - 1\right|\right| \leq 0.1 , \qquad (13)$$

adjustment of flow will be sufficient. If this criteria is isolated, then redesign of the sub-branch(s) would be required by stepping down the appropriate duct diameters. This process would be carried out until the end of the system is reached. At this point, the output of the computation would be the pressures and flow rates of all components of the system. In addition, a figure of merit for the design should be provided. This figure of merit is the product of the total flow rate and the total pressure drop. It is important to store all calculated data, i.e., flow rates, pressure losses, duct sizes and figure of merit.

After this first pass, several strategic moves can be undertaken to improve upon the system. If the relocation of exhaust points is possible, relocating the highest pressure loss branch closest to the system endpoint would be the easiest step to improve the figure of merit of the system. If such a move is not possible, relocating the entry of the high resistance branch by feasible extension of ductwork may be considered. In addition, changes in some or all of the design criteria may be considered. Any and all of these changes would then be entered, the computer keeping the previously entered values as default entries, unless changed. In the second pass the program should be so designed that it would perform only the calculations on the points past the hierarchically topmost new entry and adjust all unaffected subsequent branches by the acceptance criteria given in equation 13. The new set of calculations will result in a new figure of merit. At this point it is useful to provide an option to save the newly calculated values even if there is no significant improvement upon the previous figure of merit. Otherwise, the program may be designed to compare the newly achieved figure of merit with the previously calculated one and if there is no significant improvement to ignore these calculations, otherwise to write the results over the previous ones.

Theoretically, the branching can be of any dimension. However, it is unlikely that a system which requires more than six dimensions will be encountered in design. Consequently, all of the variables and invariant parameters for a design program may be set in an at most six dimensional array environment. As a programming tool all nominal flow rates should be initialized to zero, because this initializing can be used to test the highest dimension of hierarchy and reduce redundant searches and calculations. A simple resting flow chart to achieve this is shown in Figure 2.

The first block of a program may include user defined functions, provision for conversion of input values and results from metric to American units and a table of diameter restrictions for standard duct diameters. This can be accomplished by setting simple criteria such as:

IF D $\geq$ 80 THEN STEP D BY 10
IF 30 < D < 80 THEN STEP D BY 5
IF D $\leq$ 30 THEN STEP D BY 2

In the main portion of the program, where the calculations are performed, the sequence and specific procedure of summing up losses can be accomplished by either equivalent length or by the velocity pressure method. However, these equivalent methods do not have the same computational efficiency and the velocity pressure method is about 10 to 20 percent faster in calculation of one pass in an identical system.

In general, the display of all results or the entire system would be very cumbersome. Therefore, in the output display of results for each sub-branch or branch on demand and one at a time proves to be satisfactory. Once the design is finalized, it is necessary to display the entire set of results in hard copy. Although much elaboration in terms of providing line drawing,

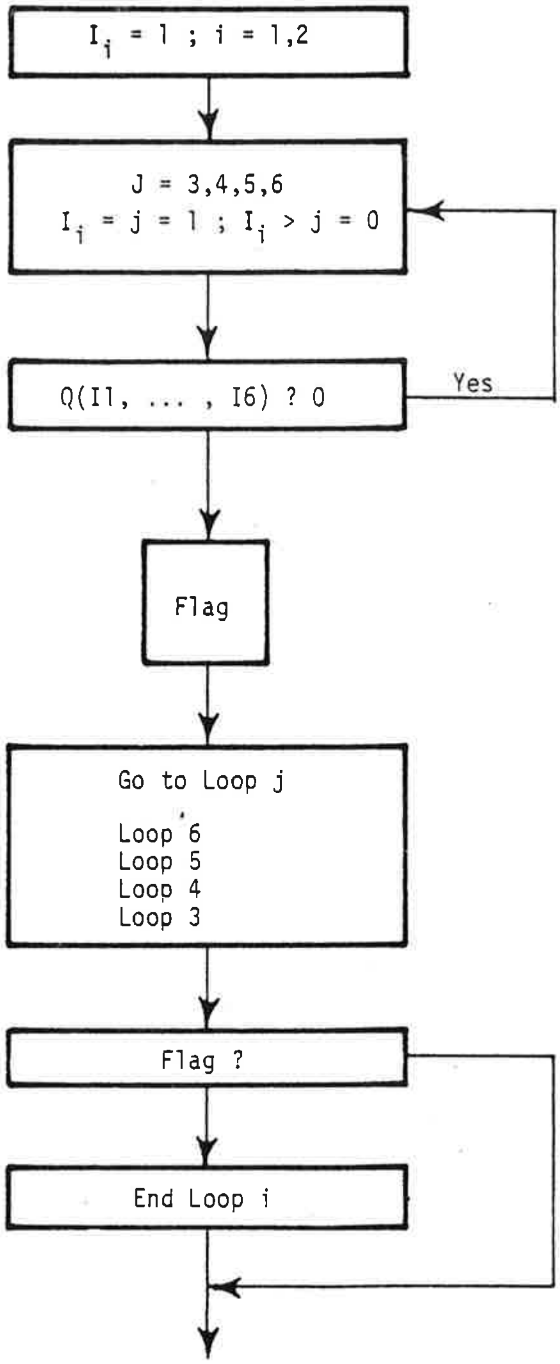


Figure 2. Flow chart for hierarchical control of calculations

etc., can be incorporated into the programming, such enhancements are not essential to the effectiveness of the program.

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