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ESTIMATED RATE OF PRESSURIZATION AND DEPRESSURIZATION OF BUILDINGS

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INTRODUCTION

A variety of engineering problems require the estimation of pressure transients in buildings. Notable examples of such problems are found in the design and safety analysis of nuclear power plants. Similar problems are faced in designing of HVAC systems for chemical plants and nuclear fuel processing facilities. Typically, a building has to be brought to a certain positive or negative pressure within a certain time. The capacity of fan required to bring this about has to be calculated. In safety evaluations, the fan has already been selected and the time required to bring the building to the desired pressure has to be calculated. Formulae for doing such calculations are not available, at least not in the books normally referred to by HVAC engineers. Hence when such calculations are needed on engineering projects, these have to be done on computers by computer analysis specialists. This generally involves considerable delay and expense.

In this paper, simple formulae developed by the author are presented which can be used to calculate pressure transients in buildings in which the temperature is approximately constant. Many practical problems fall in this category. Hence these formulae could save time and expense and help the engineers in developing better designs.

LEAKAGE DATA AND CORRELATIONS

The calculation of pressure transients in buildings requires the estimation of the rate of leakage through various leakage paths. Through experimental studies, leakage data and correlations have been developed for a variety of building components. One such source of data is the ASHRAE Handbook[1]. Ref 1 gives tabulated and graphical data for leakages through walls, doors, windows etc. The data are shown as volumetric leakage rate vs pressure difference across the component in question. Ref 1 further notes that the infiltration through a wall component can be expressed as follows:

$$q = C\ P^n \tag{1}$$

where C is the flow coefficient and the exponent n varies between 0.5 and 1, usually near 0.65.

Extensive measurements of leakage rates through a wide variety of structural components were carried out by Koontz et al[2]. The components tested included structural components such as doors and louvers as well as materials such as caulking compounds, gaskets, and paints. They found that the leakage rates through all items tested by them could be accurately correlated by the equation:

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$$q = a\,P + b\,P^{1/2} \tag{2}$$

Ref 2 lists the values of the flow coefficients a and b for a wide variety of building components.

Two limiting cases of Eq 2 may be mentioned. If b = 0, Eq 2 becomes:

$$q = a\,P \tag{3}$$

If a = 0, Eq 2 becomes:

$$q = b\,P^{0.5} \tag{4}$$

In Eq 1 to 4, P is the absolute value of pressure difference and a, b, and q are always positive. Eq 4 applies to those components which can be modelled as orifices, while Eq 3 is for capillary model.

DEVELOPMENT OF FORMULAE

Formulae are now developed for some of the cases of practical interest. In all the cases analyzed, the assumption is made that the temperature inside the building is constant. While the case of varying building temperature is also of practical interest, it is more complex and will be dealt with in a seperate paper.

Formulae for the following cases have been developed:

1. Air forced in (or forced out) at constant mass flow rate. Air leakage according to Eq 2.
2. Air forced in (or forced out) at constant mass flow rate. Air leakage according to Eq 3.
3. No forced flow of air. Air leaking in or out according to Eq 2.
4. No forced flow of air. Air leaking in or out according to Eq 3.
5. Air forced in (or forced out) at constant mass flow rate. Air leakage according to Eq 4.
6. No forced flow of air. Air leaking in or out according to Eq 4.

Formulae for cases 3, 4, and 6 (no forced flow of air) have been presented by Koontz et al[2]. They are independently derived here in a somewhat different form.

Solution for Case 1

Consider a building (or any enclosure) with a fixed internal volume V. Air is being forced into the building at a constant mass flow rate G. Let p be the pressure in the building at any instant. There are a number of leakage paths in the building structure, leakage through each being expressable by Eq 2. Let a_1, a_2-----a_n, and b_1, b_2----b_n be the flow coefficients of the various leakage paths. Then the total through all components is expressed as:

$$q_L = (a_1 + a_2 + \cdots + a_n)\,(p - p_0) + (b_1 + b_2 + \cdots + b_n)\,(p - p_0)^{0.5} \tag{5}$$

By putting $A = \Sigma\, a_j$, and $B = \Sigma\, b_j$

$$q_L = A\,(p - p_0) + B\,(p - p_0)^{0.5} \tag{6}$$

Consider a short time interval dt. This time interval can be made as small as we please. Hence while Eq 5 is for steady state, it can be applied to the time interval dt. The mass balance equation can then be written as:

$$- G\, dt + \rho_r\, q_L\, dt = - V d\rho \tag{7}$$

In Eq 7, ρ_r is the air density to which the flow coefficients a and b refer.

Differentiating the ideal gas equation with temperature remaining constant:

$$d\rho = \frac{dp}{RT} \tag{8}$$

Substituting in Eq 7 and rearranging:

$$\frac{dp}{G - \rho_r \left[A\,(p - p_0) + B\,(p - p_0)^{0.5}\right]} = \frac{RT}{V} dt \tag{9}$$

The left hand side of Eq 9 can be easily converted to a form for which the integral is available in standard integration tables. Integrating Eq 9 with the condition $p = p_i$ and $P = P_i$ at $t = 0$, the solution is:

$$t = \frac{V}{RT\,\rho_r\,A} \ln \left[\frac{G - \rho_r\,(AP_i + BP_i^{0.5})}{G - \rho_r\,(AP + BP^{0.5})}\right] + \frac{VB}{RT\,AK^{0.5}} \ln \left[\frac{\rho_r\,(2AP_i^{0.5} + B) + K^{0.5}}{\rho_r\,(2AP^{0.5} + B) + K^{0.5}} \cdot \frac{\rho_r\,(2AP^{0.5} + B) - K^{0.5}}{\rho_r\,(2AP_i^{0.5} + B) - K^{0.5}}\right] \tag{10}$$

where
$K = (4AG\,\rho_r + \rho_r^2\,B^2)$. Eq 10 is valid only if $K > 0$.

A, B, and G are always positive and hence this term cannot be negative. If B and G are both zero, this term would be zero and Eq 10 would be inapplicable. Furthermore, Eq 10 is clearly inapplicable if $A = 0$ as the right hand side becomes indeterminate. To avoid possible errors, it is advisable to use Eq 10 only when A, B, and G are not zero. The formulae presented later are to be used for these cases.

Eq 10 was derived assuming that air was being forced into a building which was at a pressure higher than that outside. It can be shown easily that it also applies to the case when air is being exhausted from a building whose pressure is lower than that outside. Care must however be taken to note that the signs of A, B, P, P_i, and G remain the same for both cases.

<u>Solution for Case 2</u>

This case is the same as case 1 except that $B = 0$. In other words, leakage rate is expressed be Eq 3. The solution for this case can be obtained by substituting $B = 0$ in Eq 10. However, a separate derivation is given here:

$$- G\, dt + \rho_r\, A\, (p - p_0)\, dt = - V d\rho \tag{11}$$

Using Eq 8 and rearranging:

$$\frac{RT}{V} dt = \frac{dp}{G - \rho_r\, A\, (p - p_0)} \tag{12}$$

Integration of Eq 12 with the condition $p = p_i$ when $t = 0$ yields.

$$t = \frac{V}{RT\ \rho_r\ A}\ \ln\left[\frac{G-\rho_r\ A\ P_i}{G-\rho_r\ A\ P}\right] \qquad (13)$$

Solution for Case 3

In this case $G = 0$ and leakge follows Eq 2. Solution is obtained by inserting $G = 0$ in Eq 10 as:

$$t = \frac{2V}{\rho_r\ RTA}\ \ln\left[\frac{AP_i^{0.5} + B}{AP^{0.5} + B}\right] \qquad (14)$$

Solution for Case 4

In this case $G = 0$ and leakage follows Eq 3. The solution for this case is obtained from Eq 13 putting $G = 0$ as:

$$t = \frac{V}{RT\ \rho_r\ A}\ \ln\left[\frac{P_i}{P}\right] \qquad (15)$$

It is interesting to note that substituting of $B = 0$ in Eq 14 also yields the same results. However, this amounts to putting $K = 0$ in Eq 10 which is mathematically incorrect. Hence derivation has been made from Eq 13.

Solution for Case 5

In this case, $A = 0$ and hence leakage is according to Eq 4. The mass balance equation is:

$$-\ Gdt + \rho_r\ B\ (p-p_0)^{0.5}\ dt = -\ \frac{Vd\rho}{RT} \qquad (16)$$

Seperation of variables and integration yields:

$$t = \frac{2V}{RT}\left[\frac{P_i^{0.5} - P^{0.5}}{\rho_r\ B} + \frac{G}{\rho_r^2\ B^2}\ \ln\frac{G-\rho_r B\ P_i^{0.5}}{G-\rho_r B\ P^{0.5}}\right] \qquad (17)$$

Solution for Case 6

In this case, $A = 0$ and $G = 0$. The solution for this case is obtained by putting $G = 0$ in Eq 17 as:

$$t = \frac{2V}{RT\ \rho_r\ B}\ (P_i^{0.5} - P^{0.5}) \qquad (18)$$

DISCUSSION ON FORMULAE

In deriving the formulae presented in the foregoing, the assumption was made that G was constant. This assumption closely approximates the situation in practical HVAC systems. Consider a fan drawing air from outside and discharging it into the building in order to pressurize it. As the pressure in the building rises, the volumetric flow rate of fan would tend to decrease. However, the increase in building pressure is generally a small fraction of the overall system pressure drop to be overcome by the fan. Hence the assumption of constant flow rate generally involves very little error. In special cases where enclosures have to be raised to pressures high enough to significantly reduce the fan output, these formulae should be applied successively over small ranges of pressure changes using the appropriate values of G.

All the foregoing formulae were derived for the case when air is leaking out af a pressurized building. However, these are also applicable to the case where air is leaking into a building which is at a pressure lower than surroundings. In applying these formulae, it should be remembered that the signs of P, P_i, and G are positive for both cases.

In all the formulae presented here a reference air density ρ_r has been used. This is the air density at which the flow coefficients a, b, or C have been evaluated. Thus the leakage rate correlation may be in terms of the outside air density or the standard air density and then these will be used as ρ_r. However, if the leakage rate correlation is based on the density inside the building, these formulae are not applicable. Derivations for leakage correlations in terms of inside air density can be made quite easily but such formulae have not been presented in this paper.

Generally, it is very difficult to predict the leakage rate of any building accurately. The actual leakage rate could depend strongly on the quality of construction and installation. The manufacturer may produce a high quality door, but the actual leakage will depend on how well it is installed. Furthermore, leakage rates will generally increase with age. In addition, the leakage data for many building components are unavailable. Due to these uncertainties about leakage rates, calculations with more precise mathematical models do not necessarily yield more reliable results. For an average building requiring moderate pressurization, assumption of a linear relation between leakage and pressure difference would be adequate for most practical calculations.

The formulae for all six cases have been presented as explicit in t. In many practical applications, formulae explicit in P or G are needed. While Eq 10 and 17 can not be so expressed, the other four formulae can be easily expressed as explicit in either P or G by rearrangement. The alternative forms of Eq 13, 14, 15, and 18 have therefore not be given in this paper.

All these formulae have been derived under the assumption that pressure outside the building is uniform all around and constant. However, the outside pressure changes with height and wind velocity. Furthermore, the pressure is higher on the windward side compared to the leeward side. These formulae should be used only when the effect of these variations is neglegible.

All the formulae presented here are dimensionless and hence any consistent system of units can be used.

PRACTICAL APPLICATIONS

Some practical problems for which the formulae presented earlier are useful are now discussed.

Case 1

Certain rooms and buildings in nuclear power plants have to be rapidly brought to a certain pressure below atmospheric in case of radioactive spill inside them in order to prevent excessive uncontrolled outflow of radioactivity. Examples are the annulus building surroundings many of the PWR-type reactor containments and the buildings enveloping the drywell in the BWR-type nuclear power plants. A filtered exhaust system of capacity sufficient to bring about this depressurization has to be provided. Leakage coefficients a and b of various building components are estimated using the data of Koontz et al[2] or from other sources. The required capacity of exhaust fan can then be calculated using Eq 10.

The control rooms of nuclear power plants generally require rapid pressurization following a radioactive spill outside. Eq 10 can be used for estimating required pressurization flow in the same way.

The problems discussed in the foregoing can be posed in another way. A safety analysis has to be performed to determine whether the system provided for pressurization or depressurization are adequate. Eq 10 can again be used to determine the time required to reach the desired pressure level with the available fan capacity. It is not uncommon for the performance criteria to change during the design stage or even for operating plants, and the adequacy of the existing equipment can then be evaluated with Eq 10.

Case 2

All discussion on Case 1 also apply to Case 2 except that leakage is calculated with Eq 3 instead of Eq 2. Generally Eq 3 is used where rough estimates are adequate or where more accurate leakage data are not available. For example, at the early design stage the only leakage information available may be that the building leakage shall not exceed one air change per day. In such a case, leakage may be assumed to be according to Eq 3 and Eq 13 used for estimating the required fan capacity, adding appropriate safety margin. It is of course possible that the leakage characteristics of some enclosures may actually follow Eq 3 and, in that case, Eq 13 would be the proper choice.

Case 3

This case often occurs in safety analyses of nuclear power plants. Certain potentially radioactive buildings are kept at a negative pressure by exhaust fans. In case of loss of power, the exhaust system stops and the building begins to lose the negative pressure due to leakage. It is then desired to know the time it will take for the building to reach zero pressure difference so that the emergency filtered exhaust system be designed to become operative within this time. If the leakage data are available in terms of Eq 2, Eq 15 can be used to determine the time to zero pressure difference or any other pressure difference.

Case 4

Case 4 is the same as Case 3 except that Eq 3 instead of Eq 2 is used for estimating building leakage. The reasons for using Eq 3 instead of Eq 2 are as explained for case 2.

Case 5 and 6

In these cases, the leakage is according to Eq 4. This equation is applicable to those building components which can be modelled as orifices. Examples are certain kinds of doors and roof hatches, partially open dampers and louvers. The leakage characterstics of some buildings approximate to Eq 4.

SUMMARY AND CONCLUSION

Generalized formulae for estimation of pressure transients in building and enclosures at constant temperature have been developed through integration of mass balance equations. These formulae can be used to estimate the size of fan required to achieve a certain positive or negative pressure in the building. These can also be used to determine the pressure that can be achieved by existing systems. Furthermore these formulae can be used to determine the time required to reach a certain pressure in an isolated building, e.g. after power failure. Finally, these formulae can be used not only for air but for any gas. It is hoped that these would save much time and effort in system design and safety analyses.

NOMENCLATURE

- a — Flow coefficient in Eq 2, for a particular leakage path.
- A — Sum of coefficient 'a' for all leakage paths in a building.
- b — Flow coefficient in Eq 2, for a particular leakage path.
- B — Sum of coefficient b for all leakage paths in a building
- G — Mass flow rate of air being forced in or out of the building.
- K — $= (4AG\rho_r + \rho_r^2 B^2)$
- p — Absolute pressure in the building at any instant.
- p_0 — Absolute pressure outside the building, assumed constant.

P Absolute value of pressure difference $(p-p_0)$.

q Volumetric leakage rate at air density ρ_r from a particular leakage path.

q_L Sum of volumetric leakages at air density ρ_r from all leakage paths in a building.

R Gas constant for air, 287 J/kg deg K (53.3 ft. lb_f/lb_m deg R).

T Absolute temperature inside the building, assumed constant.

ρ Density of air in the building at any instant.

ρ_r Reference air density for coefficients a and b.

t Time from start.

V Internal volume of building occupied by air.

Subscripts

i At time t = 0.

REFERENCES

1. " ASHRAE Handbook of Fundamentals," Chap. 21, ASHRAE Inc., New York, 1977.

2. Koontz R. L., et al, "Conventional Buildings for Reactor Containment," NAA-SR-10100, 1965. Available from Office of Technical Services, Department of Commerce, Washington 25, D.C.