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TORNADO DEPRESSURIZATION AND AIR CLEANING SYSTEMS

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Abstract

Results from analytical and experimental investigations of tornado depressurization effects on air cleaning systems are presented. Development and use of a computer code that simulates the internal pressures and flows within an arbitrary ventilation system is described. The formulation of fluid motion equations is based upon lumped component response, isothermal or adiabatic compression of air, and conservation of mass. A computer generated movie is shown illustrating the flows and pressures in a simple system.

Also described are experimental investigations to determine air cleaning component response to high flow rates caused by tornado depressurization. HEPA filter is the principal component under investigation. A description of the experimental apparatus is given and preliminary test results presented.

I. Introduction

Air cleaning systems in nuclear fuel cycle facilities must maintain confinement during such natural phenomena as earthquakes and tornados. The operation of a nuclear facility ventilation system is highly dependent on stable atmospheric pressure to maintain proper pressure differentials between containment zones. Atmospheric pressure drops as large as 20.7-kPa (3-psi) are associated with tornados, so that generation of undesirable pressures and flow rates within a ventilation system is possible. Large pressure drops could cause filtration failures, duct collapse or damper failures. Failure of these components in air cleaning systems could result in release of radioactive material to the environment.

Tornado depressurization effects on air cleaning systems are being studied both experimentally and analytically at the Los Alamos Scientific Laboratory and New Mexico State University. A computer code that will predict the magnitude of the pressures and flows within an air cleaning system is the objective of the analytical effort. Experimental testing has centered on evaluating critical air cleaning component response to large pressure pulses. The experimental data obtained will establish empirical relationships for the computer code, and provide structural response information. The status of the experimental and analytical work will be described in the following sections of this paper.

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II. Experimental Work

Preliminary Experimental Testing

Small-scale testing of 0.2-by 0.2-m (8-by 8-in.) HEPA filters has been performed at New Mexico State University⁽¹⁾. A blow-down system was used to impose a 20.7-kPa (3-psi) pressure differential across the test filters for three seconds. A pressurized tank (Fig. 1) supplied the air needed to create the required pressure pulse.

The mass flow rate was regulated by sonically choking the flow, and expanding to the desired pressure in a chamber. The chamber served to slow the flow and allow the prefiltering system to operate within design capacity. The flow was exited through a test section of sufficient length to achieve uniform flow before impinging upon the test filter. Flow timing was accomplished by controlling the opening rate of a pneumatically operated ball valve upstream from the sonic orifice.

New 0.2-by 0.2-m (8-by 8-in.) HEPA filters were tested at overpressures of 20.7-kPa (3-psi) with a 6.9-kPa/s (one-psi/s) pressurization rate. Characteristic flow-resistance data were obtained for the filters. The following conclusions were made from these tests.

- A pressurization rate of 6.9-kPa/s (one-psi/s) did not cause physical damage to the filters.
- In some tests, the pressurization rate was larger than 6.9-kPa/s (one-psi/s), which led to failure of the filter. The 0.6-by 0.6-m (24-by 24-in.) filters would be even more susceptible to structural failure because of their larger span.
- At high flow rates the pressure drop across the filter depends upon the duct cross-sectional area, and not on filter depth (Fig. 2).
- Air seems to pass through only a small portion of the filter during the pressure transient. This raises the question of filter effectiveness even if structural failure does not occur (Fig. 3).

Present Experimental Testing

The small filter experiments provided basic information for designing an experimental facility to test 0.6-by 0.6-m (24-by 24-in.) HEPA filters. Results of the small filter tests have led to speculation that high flow rates through HEPA filters can also lead to filter failure. The high velocity air through the folded ends of the fiber mat may open up mat fibers allowing high flow rate air to pass through, and then close after the transient with no evidence of structural failure. (See the change in filter resistance in Fig. 2). Entrapment of particles by the velocity-dependent diffusion mechanism may not occur during turbulent air flow through the fibers. Re-entrainment of smaller particles without a second entrapment could also occur under reversed high flow rate conditions.

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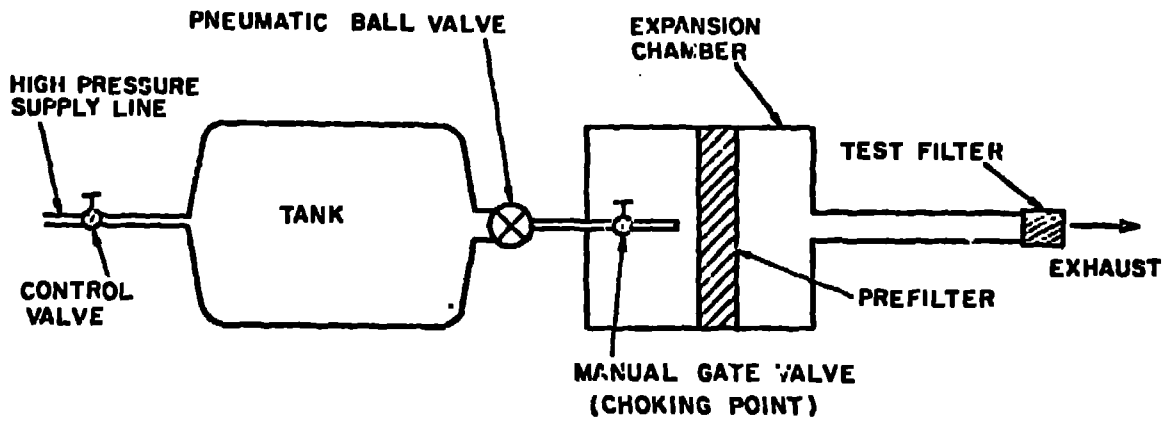


Fig. 1. Small filter experimental apparatus.

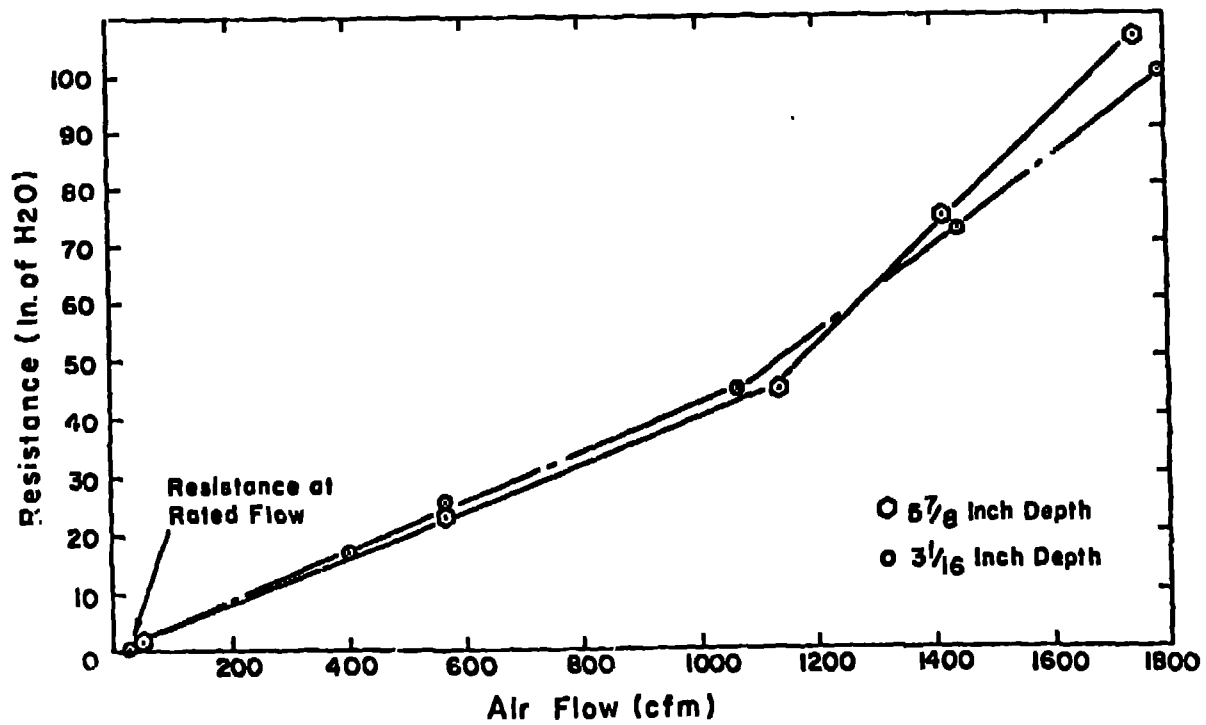


Fig. 2. Flow-resistance curve.

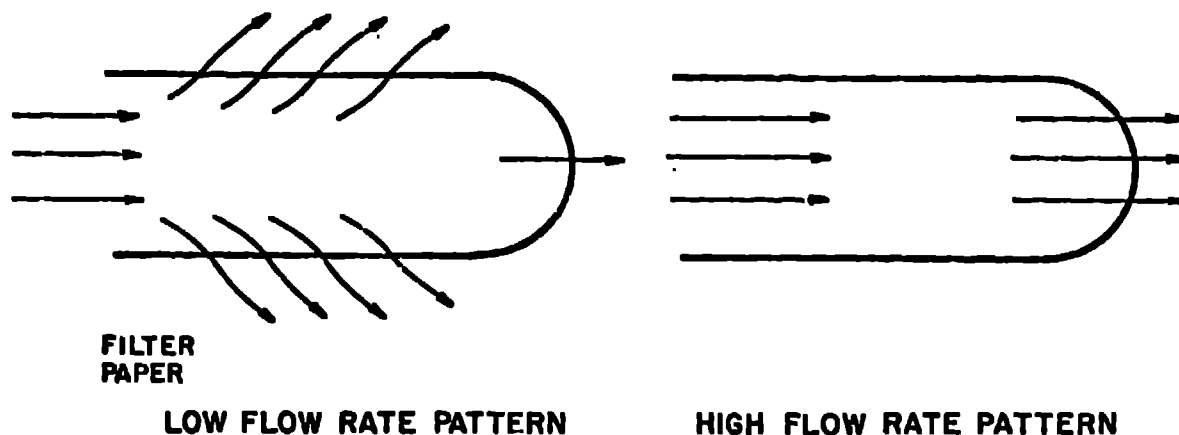


Fig. 3. Flow patterns through HEPA filter.

Objective of the present test program will be to determine the response of 0.6-by 0.6-m (24- by 24-in.) HEPA filters subjected to pressure pulses simulating a NRC Region I tornado (Fig. 4). Two possible failure modes will be investigated; failure from structural damage such that the physical integrity of the filter is destroyed and filter degradation under the NRC Region I tornado pressure conditions.

The experimental program will attempt to answer the following questions:

- Will the structural integrity of the filters be maintained during the pressure pulse?
- How critical is the rise-time of the pressure pulse? When, or at what rate of the pressure rise will the filters invariably fail?
- What is the actual flow-path through the filters during the transient pressure pulse? How does the porosity of the filters change during the pulse?
- If the filters do not fail structurally, is filter effectiveness maintained during the transient pressure pulse? Is filter effectiveness different after the pressure pulse?
- How effective are "loaded" filters during the pressure pulse? Does degree of loading have an effect upon structural failure of the filters?
- How much "release" can be expected during the transient pressure pulse for various degrees of loading?

Proposed Test Methods and Equipment. The equipment to be used to test the 0.6-by 0.6-m (24-by 24 in.) HEPA filters will be a scaled-up version of the preliminary experimental equipment. Two large pressure tanks and compressor equipment were obtained from the Nevada Test Site, and are now located at New Mexico State University at

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Las Cruces, New Mexico. The pressure tanks are each 1.5-m (5 ft.) in diameter and 19.8-m (65 ft.) long (Fig. 5). They were made to contain oxygen at pressures to 19.3-MPa (2800-psi.). The compressor is capable of supplying air at 1.7-MPa (250-psi). A pressure of 1.3-MPa (200-psi) in the tanks will provide enough air for one pressure pulse. After each pressure pulse is applied, the tanks will be re-pressurized for the next pulse.

As in the small filter experiment, the mass flow rate will be regulated by sonically choking the flow and expanding into a 3.1-by 3.1-m (10-by 10-ft.) chamber (Fig. 6). The expansion chamber will contain 25 HEPA filters for prefiltering the air. The air will travel through a duct of sufficient length to achieve uniform flow before impinging on the test filter.

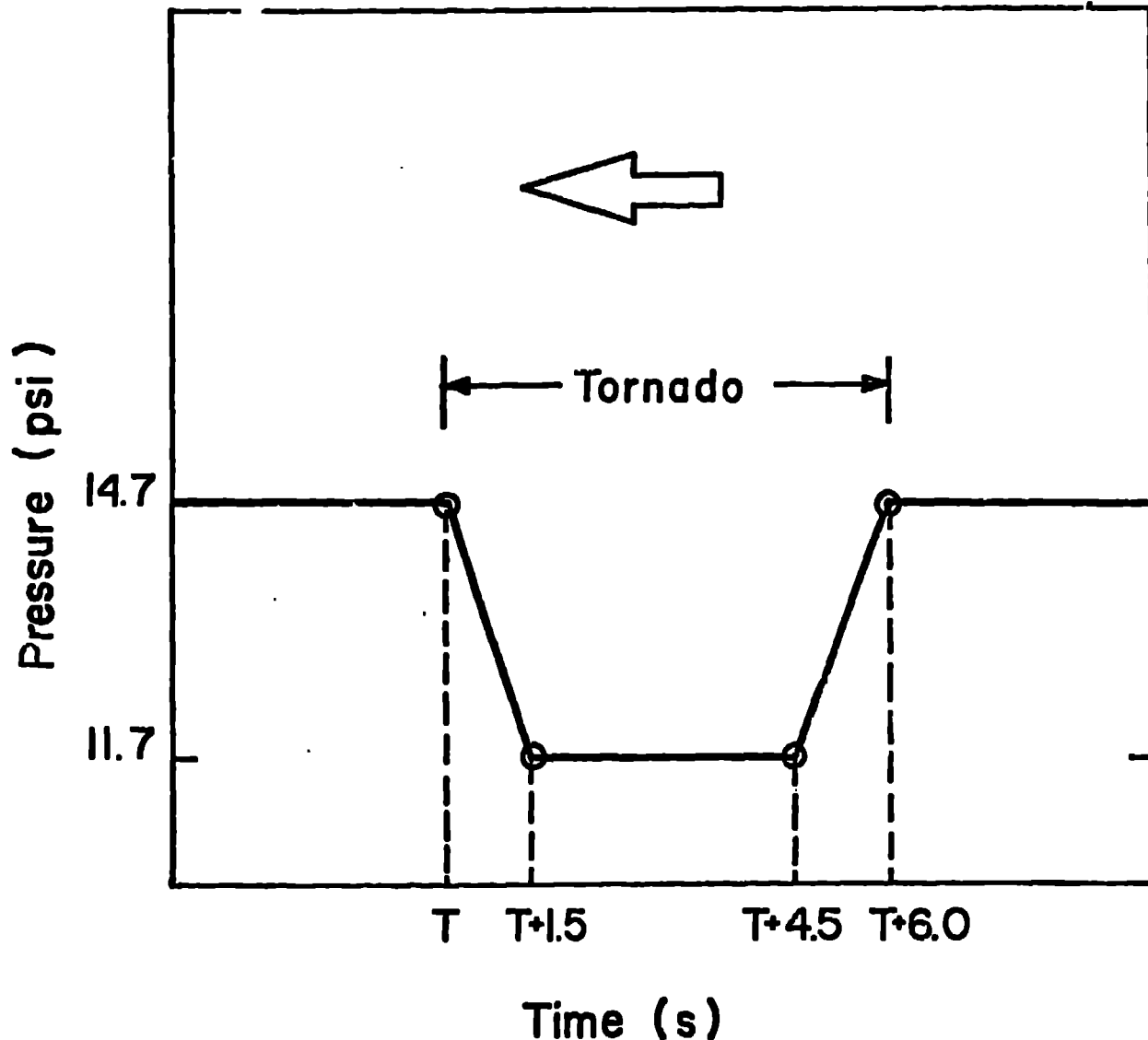


Fig. 4. Assumed pressure transient for Region I Tornado⁽²⁾.

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Fig. 5. Pressure tanks.

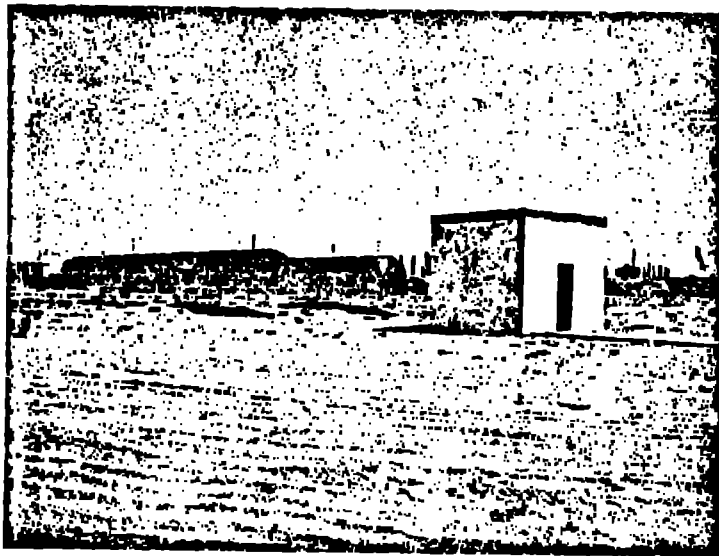


Fig. 6. Expansion chamber under construction.

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The pressure pulse rise-time will be regulated by controlling the opening rate of valves between the expansion chamber and the high pressure air supply tanks. A pneumatically operated ball valve will be used with a closely regulated air pressure to actuate the control mechanism. A multiple valve arrangement is also being evaluated to achieve pressure rise times shorter than the NRC Region I tornado of 1.5 seconds.

The key to obtaining answers on questions of effective filtration is an ability to measure filter behavior during a transient pressure pulse. This can be accomplished by injecting particles of uniform size into the supply duct upstream of the filter, and simultaneously measuring particle density upstream and downstream from the filter. Care must be taken to distribute the particles uniformly across the cross-section of the duct. Also, particles of a size and density comparable with reprocessing ventilation systems should be used.

Several methods for determining the particle density upstream and downstream of the filter during the pressure were considered. These included nuclear tracer methods, x-ray defraction methods, and light diffusion or scattering methods. The safety problems inherent with the handling of radioactive materials and x-ray equipment as well as the expense of the instrumentation needed for these methods essentially eliminated them from consideration. The further requirement that the porosity of the filter material be investigated during a transient pressure pulse virtually demanded use of a light scattering method. The fact that particle density must be measured in an airstream having a velocity of 61-m/sec (200-ft/sec) during a time interval of approximately 3 seconds led to the consideration of a Laser Doppler Velocimeter (LDV) as both a particle counter and velocity meter. A slight modification on the optical system of the LDV will allow investigation of a filter porosity using a single laser beam.

The measured particle density will be related to the number of particles passing through a small volume per unit time. The data rate measured by the LDV is proportional to the number of particles passing through its measurement volume per unit time. Hence, the difference in data rate upstream to downstream across the filter gives the filter effectiveness (F_{eff}) during the pulse.

$$F_{eff} = \frac{\text{Data Rate Upstream} - \text{Data Rate Downstream}}{\text{Data Rate Upstream}} \quad (1)$$

A possible configuration of such a system is shown in Fig. 7. We believe that the LDV system could monitor the effectiveness of clean and loaded filters during a pressure pulse. Further, it could give a quantitative measurement of particles released from loaded filters during a pressure transient.

The LDV system would give the mean flow velocity upstream and downstream of the filters, as well as the turbulence level at these points. Furthermore, by traversing the LDV measuring volume (the crossing point of the beams) across the cross-section of the duct downstream of the filters, the flow path of the air through the filters can be determined. Porosity of the filter material during the pressure pulse could be investigated by passing a laser beam through the filter and measuring the change in beam intensity.

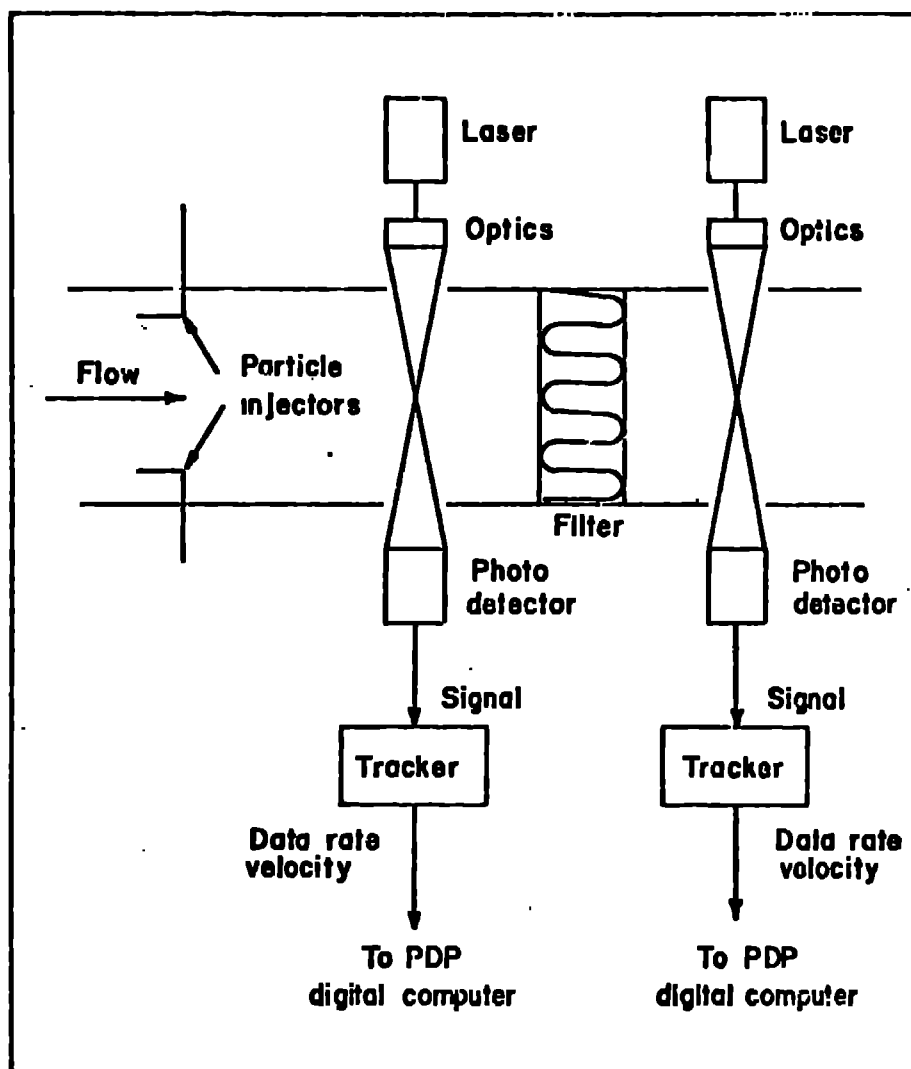


Fig. 7. Laser instrumentation system.

Future Investigations

Further investigations will examine the behavior of other ventilation system components during tornado induced pressure transients. Considerable uncertainty exists concerning the response of a fan or blower to a change in atmospheric pressure. Blowers on either the exhaust or supply side, are probably the components closest to the full impact of tornado depressurization. Blower operation under conditions of out-running flow and flow reversal are not well known.

III. Analytical Work

General

Calculation of pressures and flows, within an air cleaning system for a tornado depressurization requires solution of general fluid dynamic equations, involving the conservation of momentum

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energy, and mass. These equations are not easily solved numerically, but they do provide a basis for development of a simplified set of working equations. Analysis of these equations showing the importance of inertia and shock terms has been described elsewhere(3). Simplification and coupling of these equations with empirical fluid-flow relationships, allows development of equations that can be used to calculate the fluid dynamics in a network of connecting ducts and components.

A digital computer code "TVENT" has been developed that utilizes the equations derived in the following section to predict the transient response of arbitrary ventilation systems to tornado induced pressure transients.

Formulation of Equations

The equations are formulated using a "lumped" parameter approximation that neglects spatial distribution of variables. The following equations types will result upon application of the lumped parameter approach:

- o a simultaneous set of coupled nonlinear algebraic equations, and
- o a simultaneous set of ordinary differential equations.

The lumped parameter approach includes a number of system elements or branches joined together at points called nodes. The nodes are the connection points at the upstream and downstream ends of the branches. The pressure variable of the system is lumped into the nodes. Air cleaning system components such as dampers, filters and blowers, that have a resistive nature, are located within the branches of the system. A branch without a component (the duct work) also has a resistive nature. The frictional resistance to flow in the ductwork and system components is lumped within the branches of the network. An empirical pressure-flow relationship suitable for the elements is used for all branches in the system. This relationship can be written as:

$$Q(K) = \alpha(K) + \beta(K)(P(J) - P(I))^{\gamma(K)} \quad (2)$$

where

- K = branch K,
- Q(K) = flow rate through a branch,
- $\gamma(K)$ = constants for a particular branch,
- P(I) = pressure at node I, and
- $\alpha(K), \beta(K), P(J)$ = pressure at an upstream node J so that $P(J) > P(I)$.

Application of Eq. (2) for the system components will yield a number of forms. These forms are summarized in Table I.

At any particular time, the branch flow and the pressures at the upstream and downstream nodes are unknown. Coupling all branch equations at a particular node through use of a continuity equation, allows the flow variable to be eliminated. Only the system pressures remain to be determined. An iterative process, ideally suited for the digital computer, is used with a linearized form of Eq. (2) to

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Table I Pressure-Flow Relationships for Various Branch Components.

Branch Component	$\alpha(K)$	$\beta(K)$	$\gamma(K)$	Flow Equation	Eq. No.
Duct Friction	0	Variable	0.5	$\beta(K)(P(J)-P(I))^{\gamma(K)}$	(3)
Filter (low flows)	0	Variable	1	$\beta(K)(P(J)-P(I))$	(4)
Damper	0	Variable	0.5	$\beta(K)(P(J)-P(I))^{\gamma(K)}$	(5)
Blower (linear approximation)	Variable	Variable	1	$\alpha(K)+\beta(K)(P(J)-P(I))$	(6)

determine a pressure correction (ΔP) at each node. The process is repeated many times until the pressures at the nodes are within an acceptable tolerance.

Calculation of the pressure correction parallels Streeter's procedure for determining the pressures and flows in the steady-state portion of a water-hammer computer code⁽⁴⁾. Streeter located pumps at nodes, whereas this analysis requires all components to be located within the branch connections. In addition, this formulation is a transient analysis with allowance for storage of fluid at particular nodes. This condition requires derivation of a different algorithm for calculation of ΔP at fluid storage nodes.

The pressure correction for a node is calculated assuming that the true pressure at node I is equal to $P(I) + \Delta P$. Using this approximation, Eq. (2) becomes:

$$Q(K) \approx \beta(K) [P(J) - (P(I) + \Delta P)]^{\gamma(K)} \pm \alpha(K). \quad (7)$$

Using a binomial expansion of Eq. (7), neglecting higher order terms and considering $P(I)$ to be the value of pressure at node I for the previous iteration, Eq. (7) becomes:

$$Q(K) \approx \beta(K) [P(J) - P(I)]^{\gamma(K)} \left[1 - \frac{\beta(K) \Delta P}{P(J) - P(I)} \right] \pm \alpha(K), \quad (8)$$

or
$$Q(K) \approx A - C\Delta P. \quad (9)$$

where A and C are known constants from the previous iteration and are equal to:

$$A = \beta(K) [P(J) - P(I)]^{\gamma(K)} \pm \alpha(K) \quad (10)$$

$$C = \beta(K) \gamma(K) [P(I) - P(J)]^{\gamma(K)-1} \quad (11)$$

If $P(I) > P(J)$ *, the values of A and C become:

$$A = -\beta(K) [P(I) - P(J)]^{\gamma(K)} \pm \alpha(K), \text{ and} \quad (12)$$

*J refers to downstream node in this case.

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$$C = \beta(K)\gamma(K)[P(I) - P(J)]^{\gamma(K)-1}. \quad (13)$$

Components that have a relatively large volume such as rooms, gloveboxes, and plenums are located at the nodes. These nodes exhibit a capacity for fluid storage and are called capacitance nodes. The compressibility of the system is accounted for by allowing fluid storage at the capacitance nodes. However, in all cases the conservation of mass must hold at the nodes. For an ordinary node, with no storage or blower connection, conservation of mass yields:

$$\Sigma Q(K) = 0, \quad (14)$$

or

$$\Sigma A - \Sigma C \Delta P = 0. \quad (15)$$

Solving for the pressure correction ΔP gives:

$$\Delta P = \frac{\Sigma C}{\Sigma A}. \quad (16)$$

Equation (16) is used to determine successive pressure corrections for an ordinary node without storage. When a node is connected to a duct containing a blower, the constant $\alpha(K)$ must be added or subtracted from ΣA before the correction is calculated. In all other cases $\alpha(K)$ is equal to zero.

If only steady-state values of pressure and flow are of interest, Eq. (16) is sufficient for arriving at the correct pressures. However, during a transient, mass-in does not equal mass-out at nodes containing rooms, gloveboxes or plenums. The equation of state is used at these storage nodes in addition to the continuity equation. The equation of state can be written as:

$$P(I) = \rho RT, \quad (17)$$

where

ρ = density of air at the node,
 R = gas constant for air, and
 T = absolute temperature of the air.

Differentiation of this equation with respect to time yields:

$$\frac{dP(I)}{dt} = CF(Q_{in} - Q_{out}), \quad (18)$$

or

$$\frac{dP(I)}{dt} = CF \Sigma Q(K), \quad (19)$$

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where

$$\begin{aligned} CF &= \rho RT/V, \\ Q_{in} &= \text{flow rate into node,} \\ Q_{out} &= \text{flow rate out of node,} \end{aligned} \quad (20)$$

and V is the volume of the node under consideration.

Using finite differencing, Eq. (19) can be written as:

$$\Sigma Q(K) = \frac{1}{CF} \frac{P(I)^n - P(I)^{n-1}}{\Delta t}, \quad (21)$$

where

$$\begin{aligned} P(I)^n &= \text{present iterative value of pressure,} \\ P(I)^{n-1} &= \text{past iterative value of pressure, and} \\ \Delta t &= \text{discrete time step.} \end{aligned}$$

Substituting $P(I)^n + \Delta P$ for $P(I)^n$ in Eq. (21) yields the following equation for determination of the pressure correction at a storage node:

$$\Delta P = \frac{CF \Delta t \Sigma A + P(I)^{n-1} - P(I)^n}{1 + CF \Delta t \Sigma C}. \quad (22)$$

Eqs. (16) and (22) are incorporated within the computer code TVENT so that successive pressures are calculated until the true pressures that balance the system are obtained. After convergence has been achieved, the flows that result from the calculated pressure distribution are computed from the branch component equations.

Modeling Technique

Several facility ventilation systems were reviewed to determine the complexity of these systems and to identify typical components and subsystems (5,6). A small fictitious test-case ventilation system was devised containing many of the components and subsystems common to facility ventilation systems. This test-case ventilation system (Fig. 8 and Fig. 9) was used to test the computer code. The test-case features:

- Natural bypass around rooms,
- Recirculation similar to that used in the Westinghouse Recycle Fuels Plant,
- Combinations of series and parallel arrangements of components,
- Rooms (confinement volumes) with multiple inlets and outlets,
- Duct friction, and
- A network consisting of 30 components and 25 nodal points.

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Some components have been omitted from Fig. 8 for clarity, but are included in the schematic of Fig. 9.

A branch is defined as a connecting member between two nodes and includes only one component. Boundary conditions (pressure as a function of time) and capacitance are prescribed at nodal points. The branch and node labeling are somewhat arbitrary, however numbers may not be skipped.

Following the lumped parameter approach, all of the pressure losses for a branch are ascribed to the component contributing the largest pressure loss. Thus, the duct loss may be lumped with the damper loss characterized by Eq. (5) of Table I for Branch 1 of Fig. 9. Similarly the duct pressure loss in Branch 2 of Fig. 9 may be lumped with the filter pressure loss. An inspection of the $\gamma(K)$ Table I shows that Branch 1 is modeled more accurately than Branch 2. A branch should be added to the model if the duct pressure loss is a significant fraction of the component pressure loss.

The blower pressure-flow relationship is approximated by a series of linear segments (Fig. 10). The coefficients (Eq. (6) of Table I)

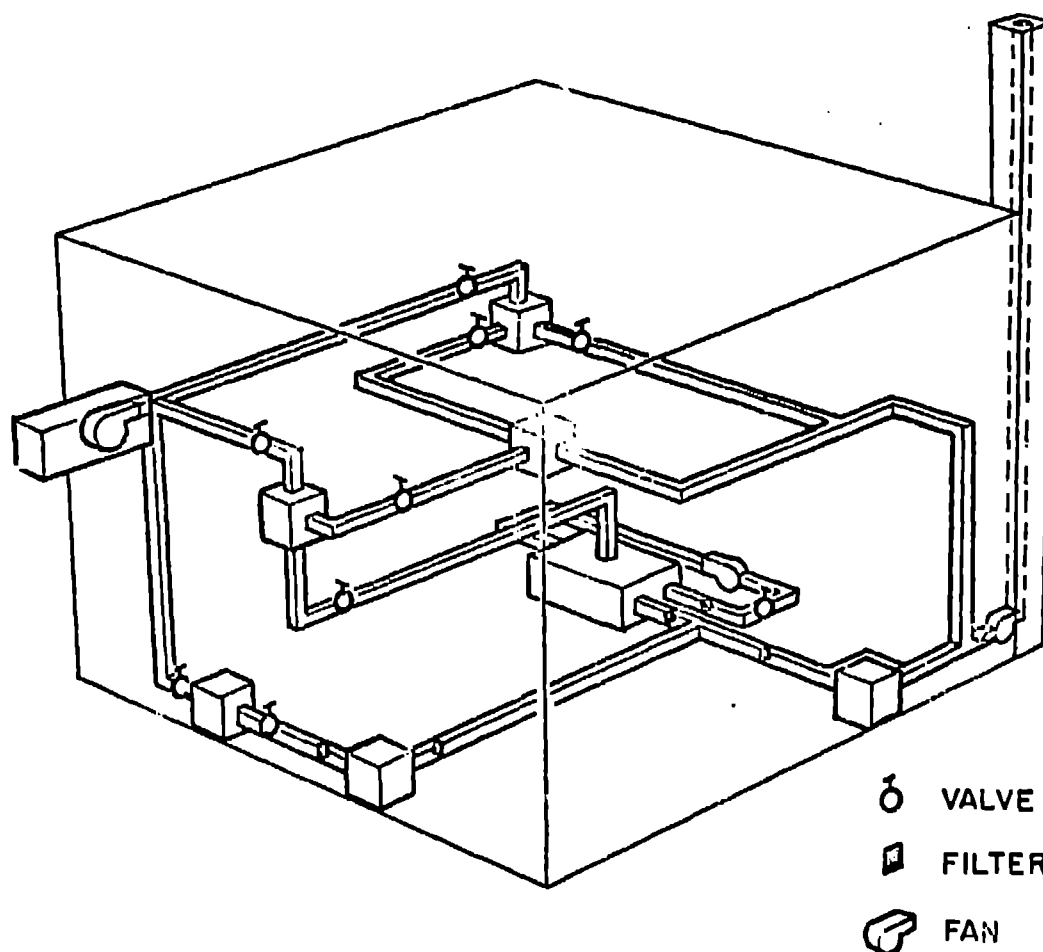


Fig. 8. Fictitious ventilation system within building.

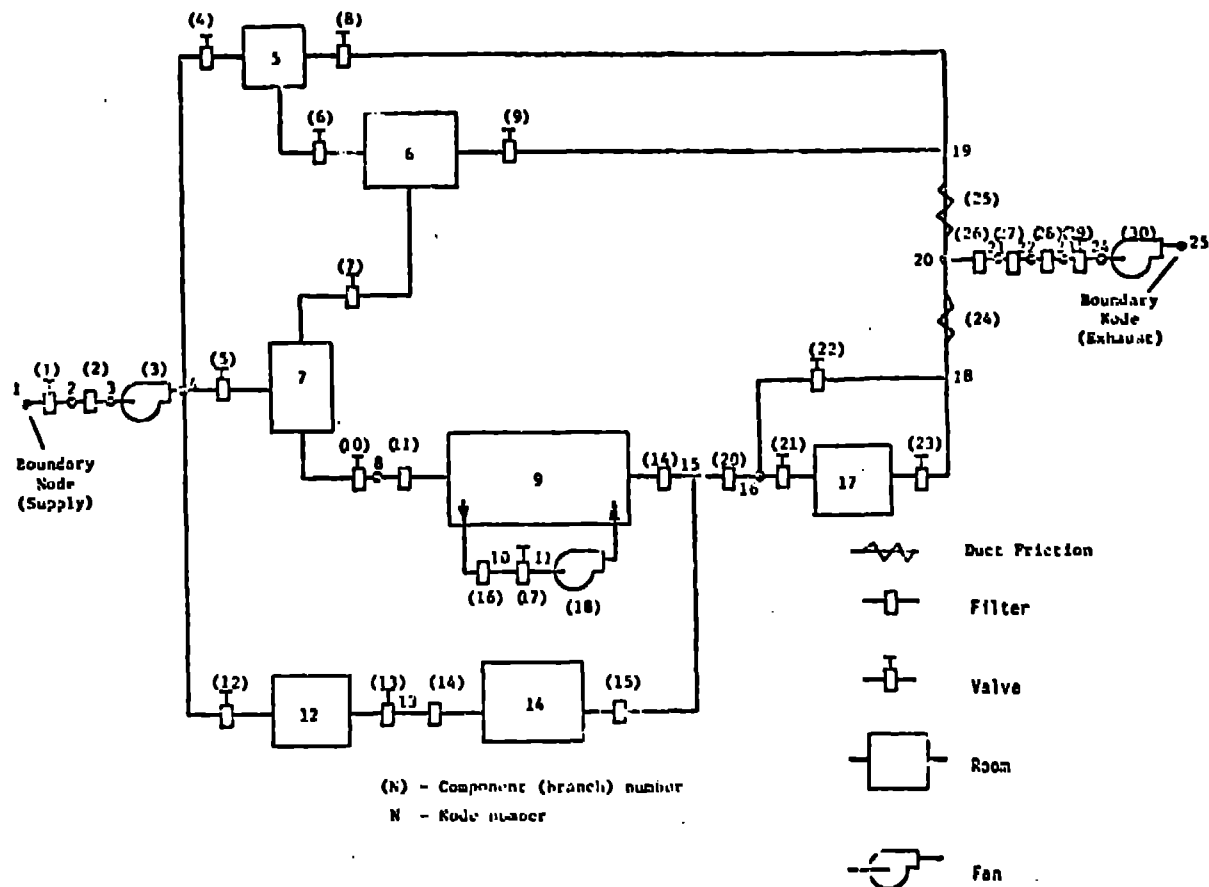


Fig. 9. Lumped parameter model of ventilation system.

are checked at every time-step and changed if necessary to obtain consistent flows and nodal pressures. This technique may also be used for filters with low and high flows as better experimental data become available.

Infiltration or leakage may be specified by the addition of a boundary node attached to a fictitious branch connected to the room with the leak. The resistance can be calculated from the design leak, the design room pressure and the boundary pressure. In this way a variable leakage rate is achieved for the transient.

Duct volumes are checked against the smallest room volume detected by the computer code. An informative message is given if a duct volume exceeds half the smallest room volume, since this would probably indicate a modeling error. Consideration should then be given to adding a capacitance node or possibly eliminating the smallest room(s).

The Computer Program "TVENT"

General. The program is written in the FORTRAN IV language and is designed to be "portable", that is, easily transferred from one computer to another with a minimum of change. Runs have been performed on the CDC 7600 computer and the IBM 360 computer to demonstrate this capability. The portability requirement precludes free format input and film plotting options that are not found on some systems.

The program is structured as a one level overlay (Fig. 11) to permit its use on smaller computers and to allow expansion.

Input. The input consists of two parts: 1) control information specifying how the problem is to be run and 2) a physical description of the system to be analyzed. An attempt has been made to organize and format the input in a way that is "natural" to the designer or engineer preparing the data for analysis. Several common methods exist for designing ventilation systems (7,8). The branch description (Fig. 12) is similar to the working tables given in the above references.

A more common method of representing the pressure-flow relationship is:

$$\Delta H = R \cdot Q^m, \quad (23)$$

where

ΔH = pressure drop across the component (measured or calculated),

R = resistance coefficient,

Q = branch design or measured flow, and

m = flow exponent (equals $1/\gamma(K)$ of Table I).

Equation (23) is used for branch description input and for calculating resistance of leakage nodes. The resistance R , if specified, overrides the resistance normally calculated by the computer using input values of pressure drop and design flow in Eq. (23). Pressures may be specified directly, in which case pressure drops are determined from these pressures and the branch descriptions.

Output. The output produced during problem set-up and transient calculations encompasses:

- Informational and diagnostic messages indicating input or modeling errors.
- Input return in the form of a card-image listing (Fig. 13) and lists associated with arrays generated from the input and used in the system solver.

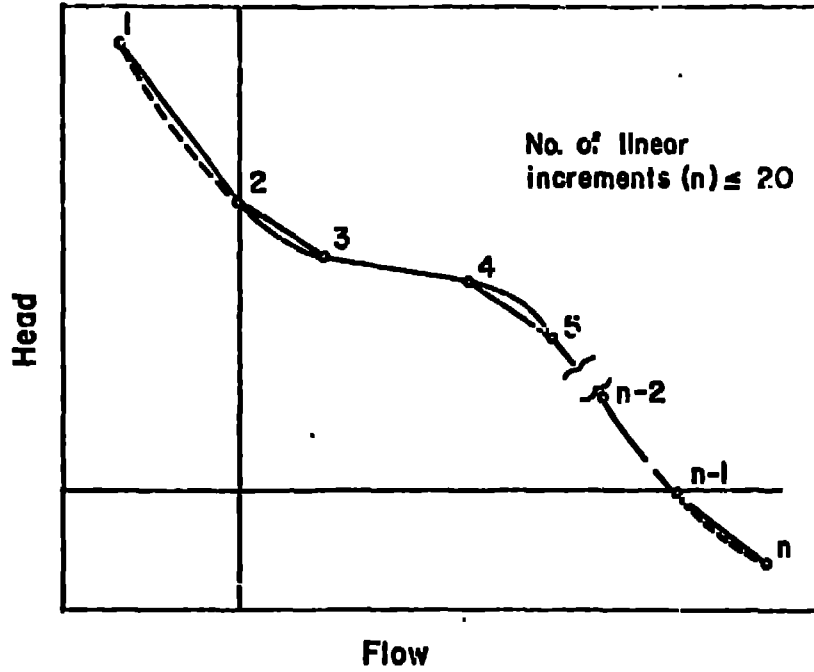


Fig. 10. TVENT blower characteristics.

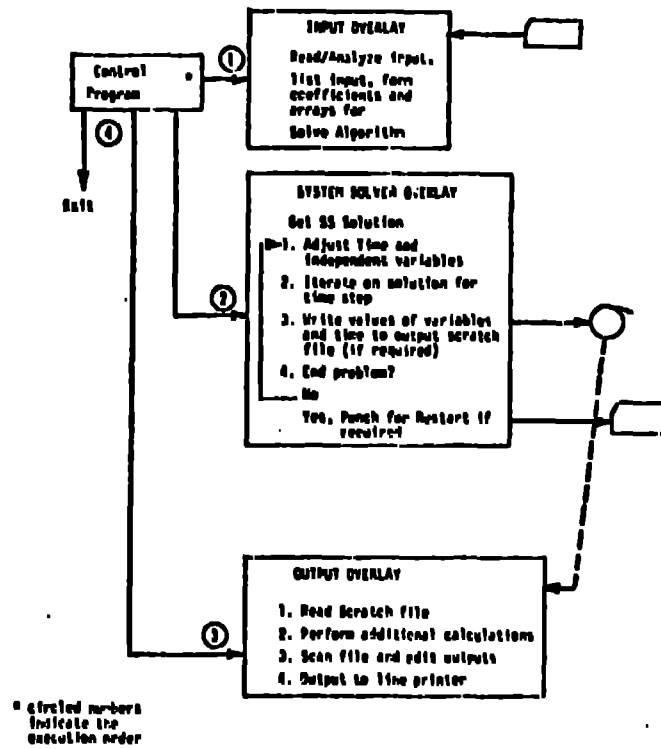


Fig. 11. TVENT program flow and overlay structure.

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NO.	IN NODE	OUT NODE	INITIAL FLOW	HYDRL RADIUS	BRANCH DATA		EXP O P	RESIST VALUE	BLOWER INTERCEPT,	INITIAL DELTA-P
					COMP	BLOWER				
					TYPE	CURVE				
1	1	2	300.000	0.000	VALV	0	.50	1.203E+03	0.	.104000
2	2	3	300.000	0.100	FILT	3	1.00	1.003E+03	0.	.307200
3	3	4	300.000	0.200	BLWR	1	1.00	2.500E+02	1.0000E+03	2.000000
4	4	5	0.000	0.000	VALV	0	.50	1.000E+02	0.	1.000000
5	4	7	156.100	0.000	VALV	0	.50	1.201E+03	0.	.016000
6	5	6	0.000	0.000	VALV	0	.50	1.200E+03	0.	.000000
7	7	6	0.000	0.000	VALV	0	.50	1.000E+02	0.	1.000000
8	5	19	0.000	0.000	VALV	0	.50	1.200E+03	0.	.007000
9	6	19	0.000	0.000	VALV	0	.50	1.200E+03	0.	.007000
10	7	8	57.400	0.000	VALV	0	.50	1.202E+03	0.	.007000
11	8	9	57.400	0.000	FILT	0	1.00	3.005E+02	0.	.191000
12	4	12	103.000	0.000	VALV	0	.50	1.200E+03	0.	.006000
13	12	13	102.000	0.000	VALV	0	.50	1.200E+03	0.	.006000
14	13	14	100.000	0.000	FILT	0	1.00	6.003E+02	0.	.103000
15	14	15	100.000	0.000	FILT	0	1.00	6.003E+02	0.	.103000
16	9	10	170.000	0.000	FILT	0	1.00	6.006E+02	0.	.257000
17	10	11	180.100	0.000	VALV	0	.50	1.201E+03	0.	.022500
18	11	9	200.000	0.000	BLWR	2	1.00	2.500E+02	2.5000E+02	.200000
19	9	15	57.000	0.000	FILT	0	1.00	3.001E+02	0.	.102000
20	15	16	100.500	0.000	FILT	0	1.00	3.000E+02	0.	.035000
21	16	17	70.300	0.000	VALV	0	.50	1.201E+03	0.	.003000
22	16	18	112.000	0.000	VALV	0	.50	1.200E+03	0.	.000000
23	17	18	00.200	0.000	VALV	0	.50	1.201E+03	0.	.000000
24	18	20	103.000	0.000	DUCT	0	.50	1.007E+03	0.	.011000
25	19	20	0.000	0.000	DUCT	0	.50	1.000E+03	0.	.050000
26	20	21	305.000	0.000	FILT	0	1.00	7.005E+02	0.	.565000
27	21	22	305.000	0.000	FILT	0	1.00	3.021E+02	0.	1.310000
28	22	23	305.000	0.000	FILT	0	1.00	3.021E+02	0.	1.310000
29	23	24	305.000	0.000	VALV	0	.50	1.200E+03	0.	.100000
30	24	25	305.000	0.000	BLWR	3	1.00	2.500E+02	1.0000E+03	2.010000

Fig. 12. Branch description of input data.

TYENT JAN 76 LABL

10 20 30 40 50 60 70 80

1234567890123456789012345678901234567890123456789012345678901234567890

A REGION I TORNAOO AT THE AIR SUPPLY

.1875 12. 4

14.3			1	2					
1			1						
25									
1	5								
			1.3		-83.867	4.5		-83.867	
			9.8						
6.									
10	25	3	7	3					
1	1	2	300.0			V	.188		
2	2	3	300.0			F	.307		
3	3	4	300.			B			
4	4	5				V	1.0	1.000E-04	1
5	4	7	156.1			V	.8169		
6	5	6				V	.02005	6.944E-07	
7	7	6				V	1.0	1.000E-04	
8	5	19				V	.007	6.944E-07	
9	6	19				V	.007	6.944E-07	
10	7	8	57.4			V	.00228		
11	8	9	57.8			F	.191		
12	4	12	100.000			V		6.944E-07	
13	12	13	100.000			V		6.944E-07	
14	13	14	100.000			F		1.430E-03	
15	14	15	100.000			F		1.430E-03	
16	9	10	170.8			F	.257		
17	10	11	100.1			V	.0225		
18	11	9	220.			B			2
19	9	15	57.9			F	.192		
20	15	16	193.5			F	.635		
21	16	17	74.3			V	.00416		
22	16	18	112.8			V	.0003		
23	17	18	80.2			V	.0046		
24	18	20	193.000			D	.0115		
25	19	23					.85	1.000E-06	
26	20	21	395.8			F	.565		
27	21	22	395.8			F	1.31		
28	22	23	395.8			F	1.31		
29	23	24	395.8			V	.188		
30	24	25	395.8			B			3
5	29.			29.					
6	20.			10.	25.				
7	20.			10.	25.				
9	20.			10.	25.				
12	20.			10.	25.				
14	20.			10.	25.				
17	20.			10.	25.				
1	2								
		4.0	1000.						
2	2								
0.0	2	1.0	250.	0.0					
3	2								
0.0	2	4.0	1000.	0.0					

Fig. 13. Card-image listing of input.

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- The following lists of steady-state and transient results as shown in Figs. 14 and 15 may be obtained (transient-output times must be requested).
 - pressures and flows for all nodal points and branches, respectively,
 - differential pressures across filters,
 - flows through filters,
 - differential pressures across dampers,
 - differential pressures between rooms, and
 - a summary of peak values.
- A limited number of pressure or flow versus time line-printer plots upon request.

Special Features.

- The input processor accepts an output frequency based on total problem-time less the problem start-restart time with additional special output times (up to 5). The latter are useful when doubt may exist whether a maximum or minimum value of some variable may have been missed.
- A problem may be stopped and subsequently restarted, which is useful for unusually large systems or long transients. It is also useful in simulating duct or filter failures during a transient.
- The input is sufficiently flexible to permit runs for verification of an existing design, and parameter studies for insight into the effects of changing design values.
- The program is easily modified. This is an asset when experimental data may dictate changes in modeling techniques.

IV. Discussion and Results

A computer generated movie has been prepared from four runs made with TVENT for the test case ventilation system.

These runs included:

1. A Region I tornado* occurs at the air supply,
2. A Region I tornado occurs at the exhaust,
3. A Region I tornado occurs simultaneously at both the air supply and exhaust, and
4. A Region I tornado occurs at the air supply, and after a six second delay appears at the exhaust.

A REGION I TORNADO AT THE AIR SUPPLY

NODAL PRESSURES FOR TIME = 6.00000

	0	1	2	3	4	5	6	7	8	9
0		0.00000	-2.29290	-4.11000	-7.39740	-1.90970	-1.90970	-0.23790	-7.05330	-5.37260
10	-5.62970	-5.65220	-0.03090	-7.24290	-5.71960	-4.83600	-2.24070	-2.13100	-2.14000	-1.44050
20	-2.11020	-2.33090	-2.05000	-3.36200	-3.37940	-0.00000				

BRANCH FLOWS

	0	1	2	3	4	5	6	7	8	9
0		1021.0	1021.0	1021.0	-234.3	1100.9	0.7	-251.6	210.0	210.6
10	-745.5	-745.5	955.2	-1065.3	-1065.3	-617.3	100.0	100.1	100.1	-161.5
20	-770.0	-397.9	-301.0	114.1	-266.9	421.5	150.6	150.7	150.7	155.1
30	155.1									

DIFFERENTIAL PRESSURE (D.P.) ACROSS FILTER

BRANCH	D. P.	BRANCH	D. P.	BRANCH	D. P.	BRANCH	D. P.
2	1.017100	11	2.400900	14	1.923300	15	.002000
16	.257300	19	.535600	20	2.596100	26	.220700
27	.511900	28	.512300				

FLOW THROUGH FILTER

BRANCH	FLOW	BRANCH	FLOW	BRANCH	FLOW	BRANCH	FLOW
2	1021.0	11	-745.5	14	-1065.3	15	-617.3
16	100.0	19	-161.5	20	-770.0	26	150.6
27	150.7	28	150.7				

DIFFERENTIAL PRESSURE (D.P.) ACROSS DAMPER

BRANCH	D. P.	BRANCH	D. P.	BRANCH	D. P.	BRANCH	D. P.
1	2.292900	4	5.407700	5	.040500	6	0.000000
7	6.320200	8	.030000	9	.030000	10	.304600
12	.633500	13	.700000	17	.022500	21	.109700
22	.130700	23	.000000	29	.016600		

Fig. 14. Composite of output listings.

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A REGION 1 TO ADD A HE AIR SUPPLY

DIFFERENTIAL PRESSURE BETWEEN ROOMS FOR TIME = 6.0000

NODE	ROOM	1	2	3	4	5	6	7
5	1	0.00000	0.00000	6.32020	3.46270	6.12120	3.00990	.22130
6	2	0.00000	0.00000	6.32020	3.46270	6.12120	3.00990	.22130
7	3	-6.32020	-6.32020	0.00000	-2.86550	-.20700	-2.51030	-6.10690
9	4	-3.46270	-3.46270	2.86550	0.00000	2.65050	.34720	-3.24140
12	5	-6.12120	-6.12120	.20700	-2.65050	0.00000	-2.31130	-5.89990
14	6	-3.00990	-3.00990	2.51030	-.34720	2.31130	0.00000	-3.50060
17	7	-.22130	-.22130	6.10690	3.24140	5.89990	3.50060	0.00000

S U M M A R Y

- HIGHEST PRESSURE OF 0.00000 OCCURS AT NODE 25
- LOWEST PRESSURE OF -0.23790 OCCURS AT NODE 7
- LARGEST POSITIVE FLOW OF 1021.00 OCCURS IN BRANCH 3
- LARGEST NEGATIVE FLOW OF -6023.30 OCCURS IN BRANCH 3
- FILTER WITH LARGEST PRESSURE DIFFERENTIAL OF 2.596100 IS IN BRANCH 20
- FILTER WITH LARGEST FLOW OF 1021.00 IS IN BRANCH 2
- DAMPER WITH LARGEST PRESSURE DIFFERENTIAL OF 6.320200 IS IN BRANCH 7
- ROOM NO. 0 HAD THE HIGHEST POSITIVE PRESSURE OF 0.00000
- ROOM NO. 3 HAD THE LOWEST NEGATIVE PRESSURE OF -0.23790

Fig. 15. Composite of output listings.

Some preliminary observations can be made based on studies of the test case ventilation system:

- A convergence tolerance of 0.025-Pa (1.0×10^{-4} in. of water) (that is nodal pressures changing by less than this amount on successive iterations) appears to be adequate for accuracy. This has been checked against different algorithms.
- Branches containing small pressure drops (less than five times convergence tolerance) exhibit significant errors. A decrease in the tolerance does not improve the solution.
- Solution accuracy is not a strong function of time-step size.
- The use of linear segments to approximate the blower characteristic curves has not caused convergence problems at those points where the algorithm might tend to search for the correct segment of the blower curve during the transient.
- The CDC 7600 computer time to real time ratio is about one half with a time step of 0.1 second for the test case problem.

V. Summary and Conclusions

The analytical and experimental investigations described in this paper will provide the analyst with some insight into the effects of tornado depressurization on air cleaning systems. The results obtained thus far are preliminary, as the analytical and experimental tools needed to investigate the problem are under development.

Interpretation of preliminary experimental results indicates that there may be a loss of material through the HEPA filters from either filter degradation or structural failure. Further experimental work at the Las Cruces Test facility will be aimed at accurately determining HEPA filter failure mechanisms under tornado conditions.

Analytical investigations with the computer code "TVENT", can provide information on overall air cleaning system response to tornado depressurization. However, this code has not been applied to an actual system. Future plans include its application to an actual system as well as incorporating experimental results for individual components. A second level of analysis using a distributed parameter approach is also planned.

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