Supply Ventilation System Design: Outside Air Duct To Return Side Of Central Fan

Armin F. Rudd
UCF/FLA Solar Energy Center

ABSTRACT

A number of systems exist for ventilation of residential buildings. In general, they can be categorized as supply, exhaust, or balanced ventilation systems. Subcategories include integration into central air distribution ducts, or single- or multi-point air distribution. This effort focused on establishing a design methodology for centrally integrated supply ventilation systems using an outside air duct to the return side of a central air distribution fan. A measurement protocol was developed, and air flow measurements were taken for 25' lengths of 5" through 9" diameter flexible ducts, with a 6" wall-cap air inlet, at duct pressures of -10 Pa to -120 Pa. Based on these measurements and other charts, a four-step design method was developed as a guide for correctly sizing the components of the ventilation system. The steps include: 1) establishing the required continuous ventilation air flow; 2) establishing a fan duty-cycle; 3) converting the continuous air flow requirement to an intermittent air flow requirement based on the selected duty-cycle; and 4) establishing the correct size outside air duct and duct pressure to give that intermittent ventilation air flow. It was found that an effective ventilation system can be achieved using a fan recycling control and a 5" to 9" diameter insulated duct from outdoors to the return side of a central air distribution fan.

INTRODUCTION

Energy efficient homes with low air leakage rates require mechanical ventilation for acceptable indoor air quality (ASHRAE 1989). A number of mechanical ventilation system types exist. These systems can be generally categorized as follows:

- Supply ventilation, with central-, single- or multi-point distribution
- Exhaust ventilation, with single- or multi-point exhaust, with or without passive inlet vents
- Balanced ventilation, with single- or multi-point supply and exhaust
- Balanced ventilation with heat recovery
- Balanced ventilation with energy recovery (heat and moisture)

Recent related publications include (Reardon and Shaw 1997), (Lubliner et al. 1997), (Sherman and Matson 1997), (Holton et al. 1997).

Supply Ventilation

Supply ventilation systems draw in outside air from a known location and deliver it to the interior living space. This known location should be selected to maximize the ventilation air quality. The air can be treated before distribution to the living space (heated, cooled, dehumidified, filtered, cleaned). If supply ventilation air is not pre-treated, it should be mixed with recirculated indoor air to mitigate discomfort effects of the outside air. Supply ventilation will tend to pressurize an interior space relative to the outdoors, causing inside air to be forced out through leak sites (cracks, holes, etc.) located randomly in the building envelope. This strategy is advantageous in warm, humid climates to minimize moisture entry into the building structure from outdoors. Care should be taken with building envelope design and workmanship when using supply ventilation in climates with cold winters.

In cold climates, interior humidity control is important to reduce condensation potential. As a first cut, areas of high moisture generation, such as kitchens and baths, should be exhausted at the source. Controlled ventilation then serves to dilute remaining interior moisture with dryer outdoor air. In some cold climate houses, depending on the building envelope design and the quality of workmanship, an exhaust fan may be advisable to balance supply ventilation air to avoid pressurizing the building.

Integrated With Central Air Distribution Fan: Outside Air Duct Into The Return Side Of A Central System Fan

Ventilation systems that provide ventilation air through a duct that extends from outdoors to the return plenum of a central air distribution fan achieve full distribution of ventilation air (Reardon and Shaw 1997), but these systems only supply ventilation air when the fan is operating. Rather than operate the central system fan continuously, which can waste energy and lead to moisture related problems in humid climates, a fan recycling control can be set to periodically distribute ventilation air during stagnant periods when there is no call to circulate air for purposes of heating or cooling. A commercially available and patented control (EDU 1997) has been developed for this application. The fan control operates the fan only after a selected delay time from the last operation of the fan. This is an energy efficiency strategy that utilizes the normal cycling of the fan, as the fan operates to distribute conditioned air in response to calls from the thermostat or humidistat, to also distribute ventilation air at the same time. Only if the fan has not operated for a specified time will the fan be operated by the fan recycling control to distribute ventilation air and provide mixing.

As a prerequisite for energy efficiency in any forced air system, the entire air distribution system must be substantially tight, including all ducts, dampers, fittings, and the air handler cabinet itself. If the ducts are leaky, the impact will be especially felt by this type of ventilation system since the runtime of the central fan will be increased.

This type of ventilation system can also provide enhanced temperature and humidity comfort control in conditioned spaces. Thermostats are typically located in a central area and are expected to serve an entire zone that usually includes closed rooms, and often, more than one floor level. Temperature conditions can vary widely between the thermostat location and extremities of the space the thermostat serves. Likewise, humidistats are usually located in a central area and suffer the same control problems. A practical solution to this could be to intermittently utilize the central air distribution fan to average the overall space conditions by mixing, while possibly at the same time supplying ventilation air. This fan recycling operation can also improve the performance of air cleaning or special filtration systems that locate the cleaning or filtration media at the return side of the central fan. Since, in this case, air cleaning can only be performed when the central air distribution fan is operating.

Some have suggested using electronically commutated (ECM) fan motors, having variable speed controls, to operate the fan at low speed all of the time to continuously draw in outdoor air for ventilation. During the cooling season, in humid climates, this running of the air distribution fan immediately after the cooling/dehumidifying apparatus has been deactivated is counter-productive, in that, moisture on the wet cooling/dehumidifying apparatus is returned to the interior space by the recirculating air. In addition, immediately after a cooling cycle, depending on the percentage of outdoor air and the outdoor humidity level, moisture could condense inside cool supply ducts. A delay should occur after a cooling cycle, wherein the fan does not operate, to allow water on the cooling/dehumidifying apparatus to drip off to the condensate drain and to allow cool supply ducts to warm up. A flow regulator, or other flow control, would also be required to assure that the right amount of ventilation air was being drawn in regardless of fan speed. Such an automatic flow regulator is available, however, this device requires at least 50 Pa pressure differential (0.2 inch water column) to operate. Depending on the fan and duct system, this much pressure may not be available even at higher fan speeds.

Single-Point Supply Ventilation Systems Using A Separate Fan

Single-point supply ventilation systems usually supply ventilation air to a location in the central area of the house. These systems usually do not achieve whole house distribution of ventilation air. Closed rooms, such as bedrooms, will probably not receive adequate ventilation air unless the central system fan operates to mix air between the central area and the closed rooms.

Alternatively, the outdoor ventilation air can be distributed through the supply ducts of the central system, but this requires that a fan be used that is powerful enough to overcome the static pressure in the supply duct when the central fan is operating, and it requires that care be taken to avoid condensation in the supply ducts in humid climates. Also, if the supply ventilation fan does not operate continuously, a back-draft damper must be installed to eliminate a large supply duct leak that would occur if the central fan operates and the supply ventilation fan does not. This system will usually not achieve whole house distribution of ventilation air when the central fan is not operating, since the supply ventilation air follow the path of least resistance, likely flowing backward to the large central area return duct.

Multi-Point Supply Ventilation Systems Using A Separate Fan

Multi-point supply ventilation systems usually supply ventilation air to a ceiling location in the central area and to all rooms of the house where a door can be closed and wherein occupants spend significant time. These systems usually do achieve whole house distribution of ventilation air (Reardon and Shaw 1997). These systems require separate ducts for distributing ventilation air only.

Exhaust Ventilation

Exhaust ventilation systems expel conditioned inside air directly to outdoors. Exhaust ventilation will tend to depressurize an interior space relative to the outdoors. This strategy can be advantageous in climates with cold winters, but care should be taken when using exhaust ventilation in warm, humid climates. Exhaust ventilation systems draw in outside air from leak sites (cracks, holes, etc.) located randomly in the building envelope. In exhaust ventilation systems, it is not possible to treat the outside air before it enters the living space since it is not known from where it is comes. The "ventilation" air could be coming from pollutant sources and cause indoor air quality problems. For instance, air drawn from cracks in a concrete slab, or a basement, or a crawl space may allow entry of insecticides, radon gas, and fungal or mold spores. In humid cooling climates, if moisture laden outdoor air enters the building envelope, and contacts cool surfaces, and is not allowed to dry to the inside, material durability and indoor air quality problems will result.

Single-Point Exhaust Systems

Single-point exhaust ventilation systems usually exhaust ventilation air from a ceiling location in the centra area of the house. They may or may not include passive air inlet vents in all room. These systems without air inlet vents in all rooms usually do not achieve whole house distribution of ventilation air, and these systems with passive inlet vents in all rooms are only marginally better (Reardon and Shaw 1997). Closed rooms, such as bedrooms, will probably not receive adequate ventilation air unless the central system fan operates to mix air between the central area and the closed rooms, or unless the closed rooms are made to be very leaky to the central area, such as in manufactured homes in the Northwest U.S.A. (Lubliner et al. 1997).

Multi-Point Exhaust Ventilation Systems Using A Separate Fan

Multi-point exhaust ventilation systems usually exhaust air from a ceiling location in the central area and from all rooms of the house where a door can be closed and wherein occupants spend significant time. These systems usually do achieve whole house distribution of ventilation air. These systems require separate ducts for distributing ventilation air only.

Balanced Ventilation

Balanced ventilation systems expel conditioned inside air directly to outdoors and supply outside ventilation air to the inside space. Balanced ventilation, by definition, should not effect the pressure of an interior space relative to the outdoors. Although, in reality the balance may never be perfect due to fluctuations in wind induced pressure and stack pressure. This strategy can be used in any climate. It is possible to filter or condition the outside air before it enters the living space.

Single-Point Balanced Ventilation Systems

Single-point balanced ventilation systems usually exhaust ventilation air from a location in the central area of the house and supply outdoor ventilation air to another location in the central area of the house. These systems usually do not achieve whole house distribution of ventilation air. Closed rooms, such as bedrooms, will probably not receive adequate ventilation air unless the central system fan operates to mix air between the central area and the closed rooms.

Alternatively, the outdoor ventilation air can be distributed through the supply ducts of the central system, but this requires that a fan be used that is powerful enough to overcome the static pressure in the supply duct when the central fan is operating, and it requires that care be taken to avoid condensation in the supply ducts in humid climates. This system will usually not achieve whole house distribution of ventilation air when the central fan is not operating, since the supply ventilation air will likely flow backward through the central area return duct.

Multi-Point Balanced Ventilation Systems

Multi-point exhaust ventilation systems usually exhaust air from a ceiling location in the central area and from all rooms of the house where a door can be closed and wherein occupants spend significant time. These systems usually do achieve whole house distribution of ventilation air. These systems require separate ducts for distributing ventilation air only.

Balanced Ventilation With Heat Recovery

Balanced ventilation systems with heat recovery operate the same as the balanced ventilation systems described above with the exception that a heat exchanger transfers heat between the exhaust air stream and the outside ventilation air stream. No moisture is exchanged between the air streams. This means that in cold months, the heating load due to ventilation will be less, and in hot months, the sensible cooling load due to ventilation will be less. The same issues relating to single-point or multi-point distribution still apply.

Balanced Ventilation With Energy Recovery

Balanced ventilation systems with energy recovery operate the same as the balanced ventilation systems described above with the exception that heat and moisture is exchanged between the exhaust air stream and the outside ventilation air stream. This means that in cold, dry months, the heating load load due to ventilation will be less, and the house interior moisture level will be higher than it otherwise would have been. In hot, humid months, the total cooling load (sensible and latent) due to ventilation will be less. A common misconception is that energy recovery ventilation systems can be used to dehumidify the interior space. Energy recovery ventilation can only keep the interior space more humid when the outside air is dry, and can only reduce the incoming moisture load when the outside air is wet. The same issues relating to single-point or multi-point distribution still apply.

Ventilation Requirements

Two code jurisdictions in the United States require whole house mechanical ventilation for homes.
One is the HUD Manufactured Home Construction and Safety Standards (HUD 1994), and the other, the Washington State Building Code Council (WSBCC 1993).

HUD Manufactured Home Construction and Safety Standards

Part 3280.103 (b) Whole house ventilation of the HUD Manufactured Home Construction and Safety Standards states:

(1) Natural infiltration and exfiltration shall be considered as providing 0.25 air changes per hour.
(2) The remaining ventilation capacity of 0.10 air change per hour or its hourly average equivalent shall be calculated using 0.035 cubic feet per minute per square foot of interior floor space. This ventilation capacity shall be in addition to any openable window area.

Washington State Building Code Council, Washington State Ventilation and Indoor Air Quality Code (Second Edition)

The Washington State Ventilation and Indoor Air Quality Code (Second Edition), Chapter 51-13 WAC, section 302.2.2 Whole House Ventilation Systems states:

> Each dwelling unit shall be equipped with a whole house ventilation system which shall be capable of providing at least 0.35 air changes per hour, but not less than fifteen cubic feet per minute per bedroom plus an additional fifteen cubic feet per minute. Whole house ventilation systems shall be designed to limit ventilation to a level no greater than 0.5 air changes per hour under normal operating conditions.

In section 304.1, Table 3-2 shows Whole House Ventilation Flow Requirements as follows:

	CFM	
Bedrooms	Minimum	Maximum
2 or less	50	75
3	80	120
4	100	150
5	120	180

It is noted that the values listed as minimums in this table are greater than the previously stipulated minimum of 15 cfm per bedroom plus 15 cfm.

In the Washington State Ventilation and Indoor Air Quality Code, Table 3-5 in section 304.1 shows Prescriptive Integrated Forced Air Supply Duct Sizing as follows:

Number of Bedrooms	Minimum Smooth Duct Diameter	Minimum Flexible Duct Diameter
2 or less	6"	7"
3	7"	8"
4 or more	8"	9"

Notes: 1. For lengths over 20 feet increase duct diameter 1 inch.
2. For elbows numbering more than 3 increase duct diameter 1 inch.

TEST PROTOCOL DESCRIPTION

A test protocol was made to establish the outside ventilation air flows for a supply ventilation system with an outside air duct connected to the return side of a central air distribution fan. Figure 1 illustrates the schematic for this system. The test protocol included the measurement of air flow through a series of outside air duct configurations at a range of negative pressures. Outside air duct configurations ranged from 5" to 6" wall jacks (outside air inlets), and from 5" to 9" flexible duct sizes. Outside air duct pressures ranged from -10 to -120 Pascal.

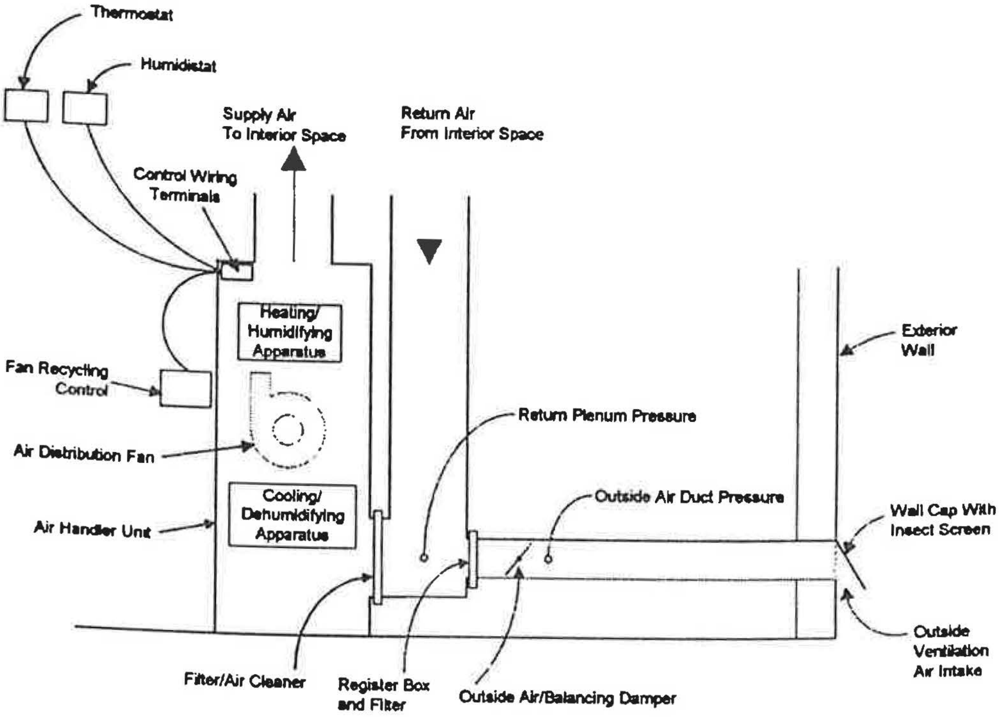

Figure 1. Diagram for a supply ventilation system using an outside air duct to the return side of a central air distribution fan.

TEST APPARATUS DESCRIPTION

All outside air ducts with the associated wall cap, balancing damper, register box, and filter were constructed using off-the-shelf components from local HVAC suppliers or builder suppliers. All flexible ducts were uncut 25' lengths. All joints between ducts and fittings were sealed with tape. A 10"x10" register box was modified with a one inch slot to hold a 12"x12" outside air filter, and was used as a transition between the flexible duct and the return plenum A calibrated fan was used to create the negative pressures and to measure air flow. Digital pressure manometers were used to measure the outside air duct pressure upstream of the balancing damper and the return plenum pressure after the outside air filter, and to measure the fan pressure which was converted to air flow by the calibration formulas. The tests were conducted inside a laboratory building to eliminate wind effects. A photograph of the test apparatus is shown in Figure 2.

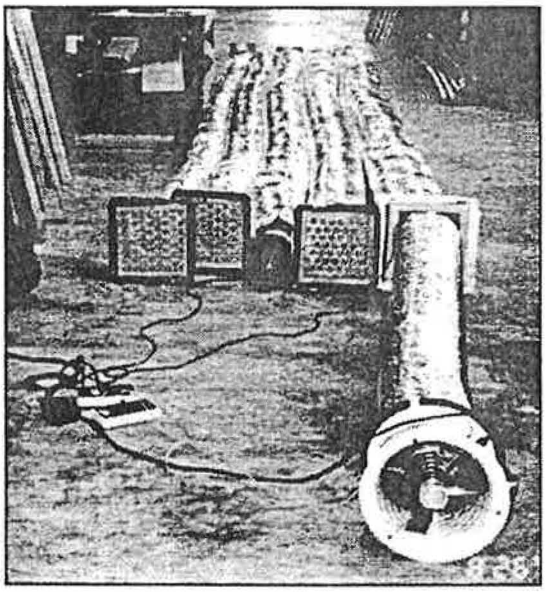

Figure 2. Photograph of testing apparatus, showing ducts and calibrated fan.

TESTING RESULTS

Figure 3 graphically shows the measured relationship between air flow and negative pressure in the outside air duct for the various duct sizes. In all cases, a 6" wall jack and the appropriate reducer, if required, was used. Table C-1, in Appendix C, lists the supporting data from which Figure 3 was created, and lists the pressure drop across the register box and outside air filter. When checking these measured air flow values against the prescriptive duct sizing requirements of the Washington State Ventilation And Indoor Air Quality Code (Second Edition), given in this report in section 2.6.2, it appears that the authors of that code assumed low outside air duct pressures, around -10 Pa. Outside air duct pressures with reasonably good duct design and duct sealing should be at least -30 Pa. If the central air distribution system return ducts are sized adequately, and if they are substantially airtight, these measurements indicate that the Washington State prescriptive outside air duct sizing may tend to cause over-ventilation.

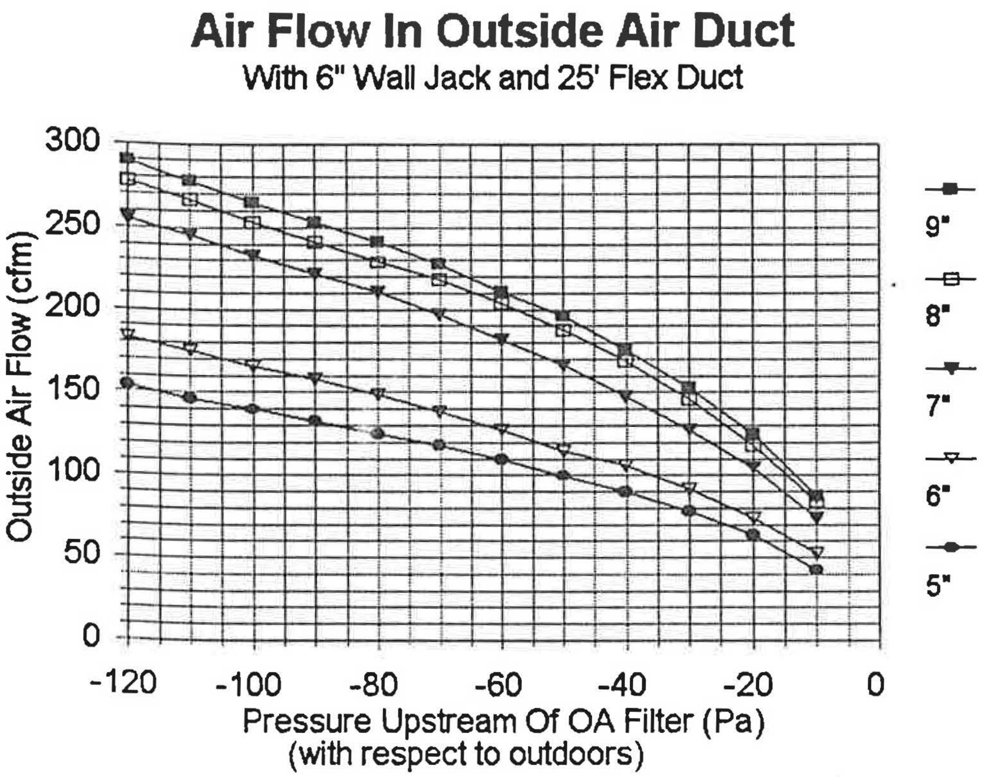

Figure 3. Air flow in outside air duct versus outside air duct pressure, for flexible duct sizes between 5 inches and 9 inches in diameter, using a 6" wall jack in all cases.

Figure 4 graphically shows, in one case, the effect of using a 5" wall jack instead of the 6" wall jack and 6x5 reducer for the 5" duct, and in the other case, shows the effect of an 8x6 reducer instead of a straight through 6" duct size. Using the 6" wall jack with the 5" duct increased air flow by an average of 9%. The 6x8 expansion into the register box reduced air flow slightly over the straight through 6" duct. The effect of this variation was small, but useful to show the measurement repeatability and sensitivity to small changes.

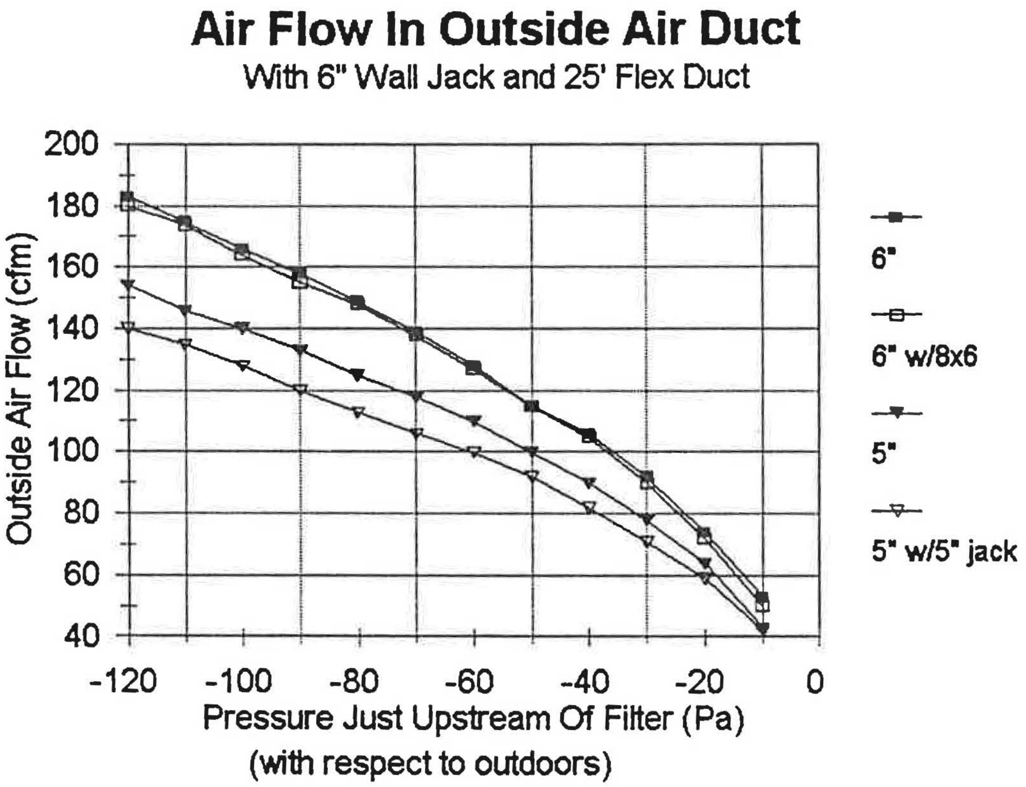

Figure 4. Measured air flow in outside air duct versus outside air duct pressure, showing the subtle differences using different duct fittings.

Charts were created to establish a methodology for selecting the amount of continuous ventilation required for a given building or occupancy. Other charts were then created to select the fan recycling time delays, and resulting duty cycle, and to select the intermittent air flow required to be equivalent to the continuous air flow selection of the first step. A summary, and example, of the entire process for using the charts follows (interpolation on all Figures and Tables is permissible):

Step 1: Using Figure 5 select the continuous outside air flow requirement for your house design as a function of the number of bedrooms, and the air flow per bedroom. Or, using Figure 6, select the continuous outside air flow requirement as a function of the air change rate you need to make up by mechanical ventilation and the house floor area.

Step 2: Using Figure 7 select the fan duty cycle based on the fan recycling delays you want to use. (Figure 7 is based on a commercially available product described in Appendix D.)

Step 3: Using Figure 8, select the intermittent outside air flow required that will be equivalent to the continuous outside air flow selected in Step 1, for the fan duty cycle you chose in Step 2.

Step 4: Using Figure 3, select the outside air duct size that will give you the required intermittent outside air flow based on the expected negative pressure upstream of the filter, or upstream of the outside air balancing damper if installed.

Number of Bedrooms In House	Continuous Outside Air Flow Based On Number Of Bedrooms Plus 1 At Listed Flow Per Bedroom (cfm/bdrm)		
	10	15	20
1	20	30	40
2	30	45	60
3	40	60	80
4	50	75	100
5	60	90	120

Figure 5. Outside air flow requirements based on the number of bedrooms plus one bedroom, at various flow rates per bedroom.

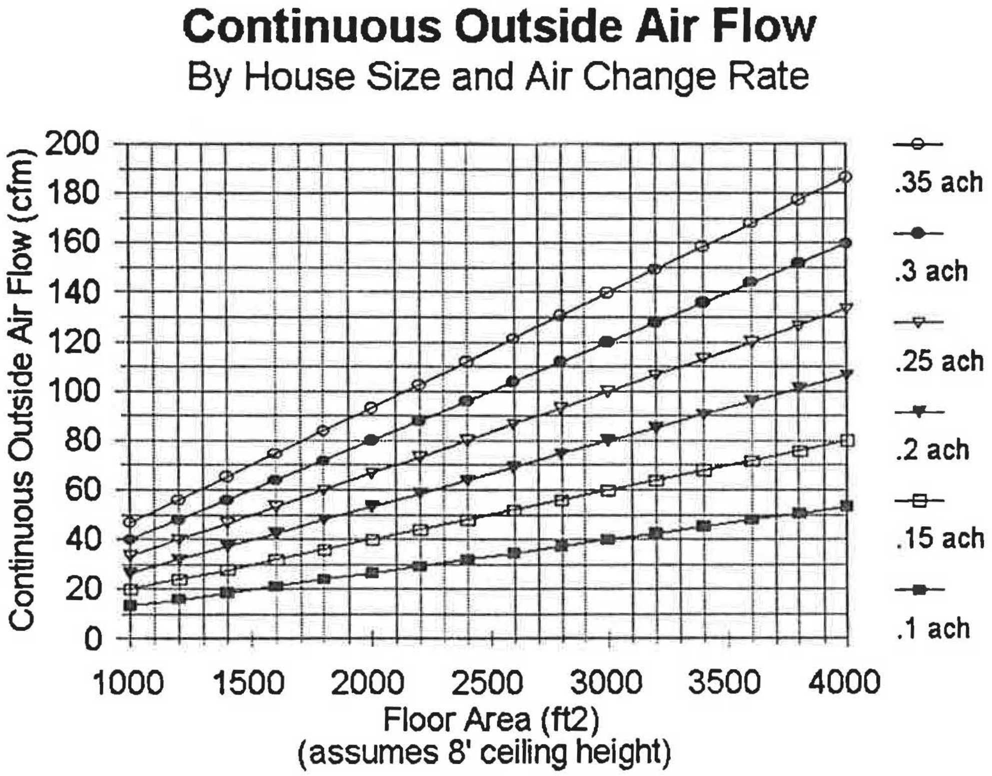

Figure 6. Continuous outside air flow versus floor area, for various air change rates.

Fan Duty Cycle (%) Based On Delay Settings

		Fan Control FAN ON Setting (min)															
		5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80
F	15	25	40	50	57	63	67	70	73	75	77	79	80	81	82	83	84
A	20	20	33	43	50	56	60	64	67	69	71	73	75	76	78	79	80
N	25	17	29	38	44	50	55	58	62	64	67	69	71	72	74	75	76
	30	14	25	33	40	45	50	54	57	60	63	65	67	68	70	71	73
O	35	13	22	30	36	42	46	50	53	56	59	61	63	65	67	68	70
F	40	11	20	27	33	38	43	47	50	53	56	58	60	62	64	65	67
F	45	10	18	25	31	36	40	44	47	50	53	55	57	59	61	63	64
	50	9	17	23	29	33	38	41	44	47	50	52	55	57	58	60	62
	55	8	15	21	27	31	35	39	42	45	48	50	52	54	56	58	59
	60	8	14	20	25	29	33	37	40	43	45	48	50	52	54	56	57
	80	6	11	16	20	24	27	30	33	36	38	41	43	45	47	48	50
	100	5	9	13	17	20	23	26	29	31	33	35	38	39	41	43	44
	120	4	8	11	14	17	20	23	25	27	29	31	33	35	37	38	40
	140	3	7	10	13	15	18	20	22	24	26	28	30	32	33	35	36
	160	3	6	9	11	14	16	18	20	22	24	26	27	29	30	32	33
	180	3	5	8	10	12	14	16	18	20	22	23	25	27	28	29	31

Figure 7. Fan duty cycle percent based on fan recycling control settings for FAN OFF and FAN ON.

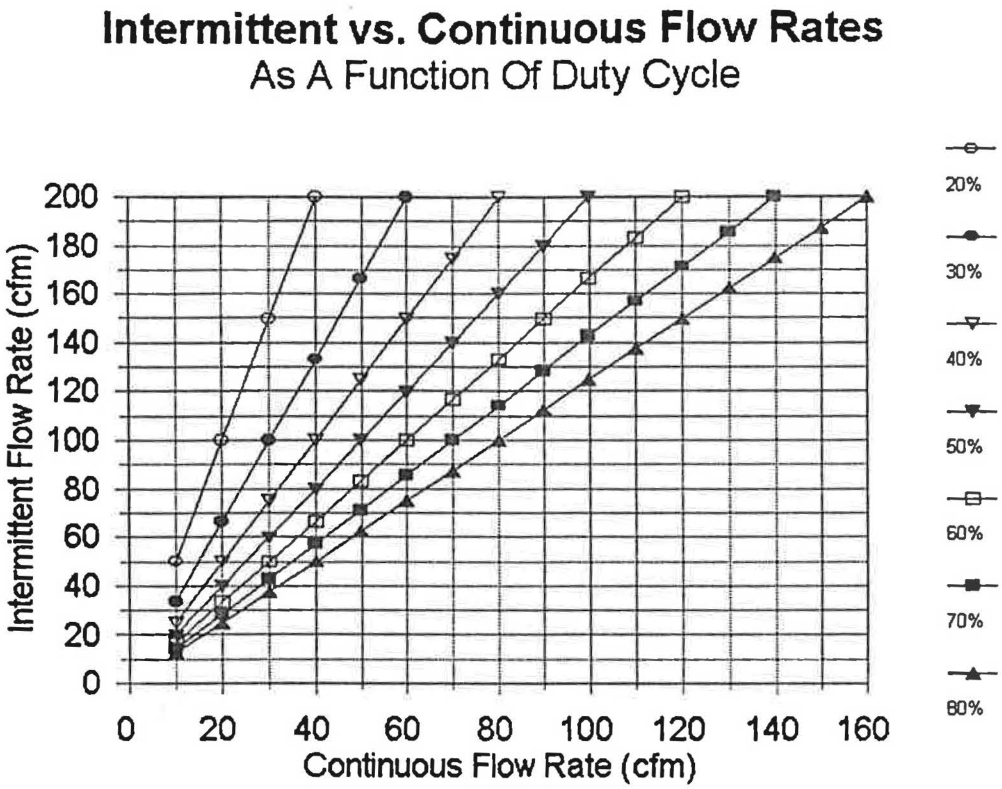

Figure 8. Equivalent intermittent air flow versus continuous air flow, for a range of fan duty cycle percentages.

An example of the procedure to size a supply ventilation system using and outside air duct and a fan recycling control connected to a central air handler unit, using Steps 1 through 4, follows:

Example Given:

Number of bedrooms = 3
Continuous ventilation air flow per bedroom = 10 cfm
House floor area = 2000 ft²
Air change rate to make up with mechanical ventilation = .15 1/h
Outside air duct pressure relative to outside = -55 Pa
Fan recycling settings: FAN OFF = 20 min; FAN ON = 10 min

Design Solution:

Step 1: From Figure 5, 3 bedrooms at 10 cfm per bedroom (plus 1) requires 40 cfm. Or, from Figure 6 (or Table A-1), for 0.15 air changes per hour (ach) and 2000 ft² floor area, 40 cfm is required.

Step 2: From Figure 7, a FAN OFF setting of 20 min, and a FAN ON setting of 10 min gives a fan duty cycle percentage of 33% (10/(10+20)*100).

Step 3: From Figure 8 (or Table B-1), for a continuous flow of 40 cfm, at a 33% fan duty cycle, an intermittent flow of 120 cfm of outside air is required for ventilation (40/0.333)

Step 4: From Figure 3 (or Table C-1), a 6" outside air duct is required for 122 cfm, at an outside air duct pressure of -55 Pa (measured just upstream of the balancing damper, or filter if no balancing damper exists)

Furnace manufacturers often require that the furnace heat exchanger be exposed to a minimum air temperature. Figure 9 shows the mixed air temperature for a supply ventilation system with an outside air duct to the central fan return plenum, with a 7% fraction of outside air flow to total air flow, for a range of indoor and outdoor temperatures. With outdoor temperature at -25 F and an indoor setpoint temperature at a conservative 66°F, the mixed at temperature at the furnace heat exchanger will be 60°F. When the furnace is on, bringing in outside air will not affect occupant comfort. However, when the furnace is off, depending on the location of supply registers, and the supply air velocity, and the sensitivity of the occupants to essentially room temperature air being circulated, comfort may be a concern (Lubliner 1997). Figure 9 includes warm outdoor temperatures to illustrate comfort related issues in hot conditions. With an outdoor temperature of 110 F and a interior setpoint temperature of 78 F, the mixed air temperature will be 80 F. It is unlikely that occupant comfort will be affected under this extreme condition, in fact, it is likely that due to the mixing of air in the entire conditioned space, the thermostat will have better feedback resulting in improved temperature control and comfort.

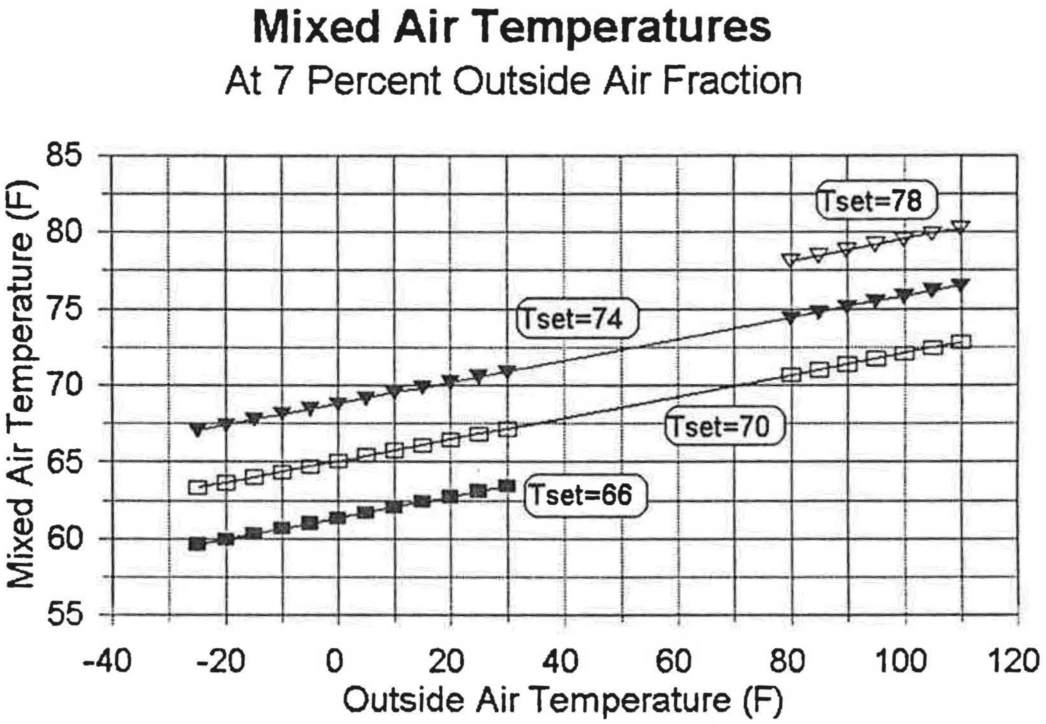

Figure 9. Mixed air temperatures for a supply ventilation system with an outside air duct to the central fan return, with 7% outside air, for a range of indoor and outdoor temperatures.

Economic analysis related to ventilation for homes was beyond the scope of this report, although future work will include that. Some economic analysis has been done by (Miller and Conner 1993), (Lubliner et al. 1997), (Sherman and Matson 1997).

CONCLUSION AND RECOMMENDATIONS

An effective ventilation system can be achieved using the fan recycling control and a 5" to 9" diameter insulated duct from outdoors to the return side of a central air distribution fan. As a prerequisite for energy efficiency in any forced air system, the entire air distribution system must be substantially tight, including all ducts, dampers, fittings, etc. and the air handler cabinet itself. Depending on the return-side fan pressure, outside air flows between 45 and 275 cfm can be achieved with 5" to 9" flexible ducts and a 6" wall jack. Outside air should be filtered before it enters the central return duct, and a balancing damper is advisable to give additional field control of the delivered outside air volume. The fan recycling control should be installed to ensure that, after the central fan has not operated for a preset time (such as when there is no call for heating or cooling), fresh air will be periodically distributed throughout the house. This fan recycling may also improve thermal comfort and the perception of air quality in rooms by evening out temperature, humidity and stuffiness conditions between rooms and the central area.

In cold climates, interior humidity control is important to reduce condensation potential. As a first cut, areas of high moisture generation, such as kitchens and baths, should be exhausted at the source. Controlled ventilation then serves to dilute remaining interior moisture with dryer outdoor air. In some cold climate houses, depending on the building envelope design and the quality of workmanship, an exhaust fan may be advisable to balance supply ventilation air to avoid pressurizing the building. A motorized outside air damper could also be used to positively disconnect outside air from the house when ventilation was not called for.

REFERENCES

ASHRAE, 1989. ANSI/ASHRAE Standard 62-1989, Ventilation for acceptable indoor air quality. Atlanta: American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc.

Energy Design Update, 1997. "Controller Improves the Efficiency of Furnace-Based Ventilation Systems." Cutter Information Corp., Arlington, MA. September.

Holton, J., M. Kokayko, T. Beggs, 1997. Comparative ventilation system evaluations. ASHRAE Transactions, Vol. 103, Part 1, pp. 731-744. Atlanta: American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc.

HUD 1994. Part 3280 Manufactured home construction and safety standards, interpretive bulletins to the standard, excerpted from the Code of Federal Regulations Housing and Urban Development.

Lubliner, M., D. Stevens, B. Davis, 1997. Mechanical ventilation in HUD-Code manufactured housing in the Pacific Northwest. ASHRAE Transactions, Vol. 103, Part 1, pp. 731-744. Atlanta: American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc.

Miller, J., C. Conner, 1997. Estimated costs of ventilation systems complying with the HUD Ventilation standard for manufactured homes. Battelle Pacific Northwest Laboratory, PNL-8947/UC-350, November.

Reardon, J., C. Shaw, 1997. Evaluation of five simple ventilation strategies suitable for houses without forced-air heating. ASHRAE Transactions, Vol. 103, Part 1, pp. 731-744. Atlanta: American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc.

Sherman, M., N. Matson, 1997. Residential ventilation and energy characteristics. ASHRAE Transactions, Vol. 103, Part 1, pp. 731-744. Atlanta: American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc.

WSBCC 1993. Washington State Ventilation And Indoor Air Quality Code (Second Edition), Chapter 51-13 WAC. Department of Community Development, Washington State Building Code Council, Olympia, Washington.

ACKNOWLEDGMENT

This project was sponsored by the U. S. Department of Energy, Office of Building Systems. We are very grateful to George James, program manager, and Richard Karney for their valued support of this work. The author appreciates the input and contributions of Philip Fairey, Subrato Chandra, and Robert Abernethy, of FSEC, and Joseph Lstiburek and Neil Moyer, of Building Science Corporation.

Appendix A

Table A-1 Continuous outside air flow required to achieve listed air change rates

House Area	House Volume	Required Continuous Outside Air Flow (cfm) To Acheive Listed Air Change Rates (1/h)					
		0.1	0.15	0.2	0.25	0.3	0.35
(ft2)	(ft3)	(cfm)	(cfm)	(cfm)	(cfm)	(cfm)	(cfm)
800	6400	11	16	21	27	32	37
1000	8000	13	20	27	33	40	47
1200	9600	16	24	32	40	48	56
1400	11200	19	28	37	47	56	65
1600	12800	21	32	43	53	64	75
1800	14400	24	36	48	60	72	84
2000	16000	27	40	53	67	80	93
2200	17600	29	44	59	73	88	103
2400	19200	32	48	64	80	96	112
2600	20800	35	52	69	87	104	121
2800	22400	37	56	75	93	112	131
3000	24000	40	60	80	100	120	140
3200	25600	43	64	85	107	128	149
3400	27200	45	68	91	113	136	159
3600	28800	48	72	96	120	144	168
3800	30400	51	76	101	127	152	177
4000	32000	53	80	107	133	160	187
4200	33600	56	84	112	140	168	196
4400	35200	59	88	117	147	176	205
4600	36800	61	92	123	153	184	215
4800	38400	64	96	128	160	192	224
5000	40000	67	100	133	167	200	233
5200	41600	69	104	139	173	208	243
5400	43200	72	108	144	180	216	252
5600	44800	75	112	149	187	224	261
5800	46400	77	116	155	193	232	271
6000	48000	80	120	160	200	240	280
6200	49600	83	124	165	207	248	289
6400	51200	85	128	171	213	256	299
6600	52800	88	132	176	220	264	308
6800	54400	91	136	181	227	272	317
7000	56000	93	140	187	233	280	327
7200	57600	96	144	192	240	288	336
7400	59200	99	148	197	247	296	345
7600	60800	101	152	203	253	304	355

Appendix B

Table B-1 Equivalent intermittent air flow based on continuous air flow requirement, for a range of fan duty cycle percentages

Continuous Air Flow	Equivalent Intermittent Air Flow At Listed Fan Duty Cycle Percentage																
	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85
10	200	100	67	50	40	33	29	25	22	20	18	17	15	14	13	13	12
20	400	200	133	100	80	67	57	50	44	40	36	33	31	29	27	25	24
30		300	200	150	120	100	86	75	67	60	55	50	46	43	40	38	35
40		400	267	200	160	133	114	100	89	80	73	67	62	57	53	50	47
50			333	250	200	167	143	125	111	100	91	83	77	71	67	63	59
60			400	300	240	200	171	150	133	120	109	100	92	86	80	75	71
70				350	280	233	200	175	156	140	127	117	108	100	93	88	82
80				400	320	267	229	200	178	160	145	133	123	114	107	100	94
90					360	300	257	225	200	180	164	150	138	129	120	113	106
100					400	333	286	250	222	200	182	167	154	143	133	125	118
110						367	314	275	244	220	200	183	169	157	147	138	129
120						400	343	300	267	240	218	200	185	171	160	150	141
130							371	325	289	260	236	217	200	186	173	163	153
140							400	350	311	280	255	233	215	200	187	175	165
150								375	333	300	273	250	231	214	200	188	176
160								400	356	320	291	267	246	229	213	200	188
170									378	340	309	283	262	243	227	213	200
180									400	360	327	300	277	257	240	225	212
190										380	345	317	292	271	253	238	224
200										400	364	333	308	286	267	250	235
210											382	350	323	300	280	263	247
220											400	367	338	314	293	275	259
230												383	354	329	307	288	271
240												400	369	343	320	300	282
250													385	357	333	313	294
260													400	371	347	325	306
270														386	360	338	318
280														400	373	350	329
290															387	363	341
300															400	375	353
310																388	365
320																400	376
330																	388
340																	400
350																	
360																	

Table C-1 Measured air flow for outside air duct supply ventilation configurations listed

Duct Size	Configuration Description	Measured Air Flow (cfm) At Listed Outside Air Duct Pressure, Just Upstream Of Filter/Box (Pa)										
		-10	-20	-30	-40	-50	-60	-70	-80	-90	-100	-110
5"	5" wall jack, 25' 5" flex duct, 5" starting collar, 10x10 ductboard box, 12x12 filter	42	59	71	82	92	100	106	113	120	128	135
	Return Plenum Pressure:	-10	-21	-31	-41	-51	-61	-70				
	dP Across Filter and Register Box:	0	-1	-1	-1	-1	-1	0				
5"	6" wall jack, 6x5 reducer, 25' 5" flex duct, 5" starting collar, 10x10 ductboard box, 12x12 filter	43	64	78	90	100	110	118	125	133	140	146
6"	6" wall jack, 25' 6" flex duct, 6" starting collar, 10x10 ductboard box, 12x12 filter	53	74	92	106	115	128	139	149	158	166	175
	Return Plenum Pressure:	-12	-23	-33	-44	-53	-64	-75	-84	-95	-106	-116
	dP Across Filter and Register Box:	-2	-3	-3	-4	-3	-4	-5	-4	-5	-6	-6
6"	6" wall jack, 25' 6" flex duct, 8x6 reducer, 8" starting collar, 10x10 ductboard box, 12x12 filter	50	72	90	105	115	127	138	148	155	164	174
	Return Plenum Pressure:	-11	-22	-33	-43	-54	-64	-74	-85	-94	-104	-115
	dP Across Filter and Register Box:	-1	-2	-3	-3	-4	-4	-4	-5	-4	-4	-5
7"	6" wall jack, 7x6 reducer, 25' 7" flex duct, 8x7 reducer, 8" starting collar, 10x10 ductboard box, 12x12 filter	74	105	128	148	167	182	197	211	222	233	246
	Return Plenum Pressure:	-13	-24	-35	-47	-58	-69	-80	-89	-99	-110	-121
	dP Across Filter and Register Box:	-3	-4	-5	-7	-8	-9	-10	-9	-9	-10	-11
8"	6" wall jack, 8x6 reducer, 25' 8" flex duct, 8" starting collar, 10x10 ductboard box, 12x12 filter	84	118	146	169	188	204	218	229	241	253	267
	Return Plenum Pressure:	-14	-26	-38	-50	-63	-74	-86	-97	-109	-119	-130
	dP Across Filter and Register Box:	-4	-6	-8	-10	-13	-14	-16	-17	-19	-19	-20
9"	6" wall jack, 9x6 reducer, 25' 9" flex duct, 9" starting collar, 10x10 ductboard box, 12x12 filter	88	125	153	176	196	211	228	241	253	265	278
	Return Plenum Pressure:	-15	-28	-40	-53	-66	-76	-90	-100	-113	-126	-137
	dP Across Filter and Register Box:	-5	-8	-10	-13	-18	-16	-20	-20	-23	-26	-27
NOTES	1. A tight 360 degree turn, or two 90 degree turns lowered the flow rate by about 3 percent											