Ventilation Strategies for Energy-Efficient Production Homes

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ABSTRACT

The Environmental Protection Agency's (EPA) ENERGY STAR® Homes program seeks to reduce greenhouse gas emissions by encouraging U.S. production home builders to voluntarily improve the thermal quality of their construction by minimizing infiltration, improving insulation, and right-sizing HVAC equipment. Tight homes need active ventilation to maintain indoor air quality, but mechanical ventilation increases initial home cost as well as operating costs. We were asked to recommend ventilation systems that minimize installation costs without jeopardizing occupant safety, indoor air quality, or operating cost savings. We evaluated nine ventilation systems in four climates by comparing annualized capital costs, annual operating costs, distribution of ventilation air within the home, potential for depressurization, and potential ventilation-related condensation in exterior walls.

Based on our analysis, we recommend *Multi-port supply* ventilation in all but cold climates, because it provides the safety and health benefits of positive indoor pressure, as well as the ability to filter air. In cold climates we recommend that *Multi-port supply* be balanced by *Single-port exhaust.* We recommend that forced-air heating and cooling systems not be used for supply ventilation unless forced-air ducts are well-sealed and/or within conditioned space, and the forced-air fan automatically operates at least 10 minutes each hour for ventilation.

Introduction

As awareness and concern about global climate change grows, so does the demand in all parts of the country for homes that require less fossil-fuel energy to heat and cool. Home thermal quality is achieved in part by reducing infiltration below the level of indoor air changes recommended by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) to maintain occupant comfort and health. Therefore, mechanical ventilation has become a residential design issue.

The Environmental Protection Agency's (EPA) ENERGY STAR Homes program encourages residential developers (i.e., production builders), who construct the vast majority of new U.S. homes, to voluntarily exceed the requirements of the Model Energy Code. ENERGY STAR homes are expected to have average annual infiltration rates of 0.15–0.20 air changes per hour (ACH), which is well below the 0.35 ACH level recommended by ASHRAE. Therefore, these homes need mechanical ventilation systems that regularly replace indoor air with outdoor air. The EPA is concerned about both indoor air quality and home thermal performance, and the ENERGY STAR Homes program is an excellent opportunity to educate residential contractors and home buyers about differences in installation costs, operating costs, and the overall performance of various residential ventilation systems. We were asked to recommend the most appropriate ventilation strategies for new, low-infiltration production (i.e., site-built tract) homes in four climates: cold, mixed (hot and cold), hot humid, and hot arid.

Background

Like many energy-efficient construction practices, residential ventilation systems were initially developed in cold climates by builders who realized that it costs less to tighten a building's shell and provide mechanical ventilation than to heat excessive amounts of infiltration air (ESB 1995). However, ventilation systems designed for homes in cold climates are not necessarily suitable for homes in the cooling-dominated South and Southwest, where most new U.S. homes are being built. Furthermore, mechanical ventilation of homes is relatively uncommon in parts of the sun belt, where many residential builders, HVAC contractors, and home buyers equate "ventilation" with bathroom spot exhaust fans (which *intermittently* exhaust moisture and odors) or forced-air systems (which condition and recirculate, but do not *exchange* indoor air). However, bathroom exhaust and forced-air conditioning systems were not designed, and are not necessarily most suitable, for house ventilation. Recent improvements in the noise level, efficiency, and longevity of ventilation fans and in the variety of controls and air filters have provided us an opportunity to optimize the design and performance of residential ventilation systems.

A basic home ventilation system consists of at least one fan, ductwork connecting the fan to the outdoors and/or living space, and controls. Fans used for ventilation should be quiet (less than 1 sone),[1] efficient (>10%), and designed for long life (≥ 10 yrs) under continuous (non-stop) or continual (regular interval) operation. Ductwork used for ventilation should be UL181-rated and designed according to Air Conditioning Contractors of America (ACCA) Manual D, with minimal duct length and resistance to airflow; ducts located outside (and some located within) conditioned space should be sealed and insulated (ACCA 1995). Suitable ventilation system controls include a low-high speed switch and/or a programmable timer that allows occupants to vary the rate (in cfm) of ventilation. System design should account for the house size and the internal resistance of the ventilation system. Operation of a residential ventilation system should be automatic; residents should not have to think about their ventilation system, except perhaps to occasionally boost the ventilation rate (Stevens 1996).

There are three basic types of residential ventilation systems: exhaust, supply, and balanced. Exhaust systems use a fan to pull indoor air out of a house, supply systems use a fan to push outdoor air into a house, and balanced systems use two fans that exhaust and supply similar volumes of air. Table 1 lists the three exhaust, three supply, and three balanced ventilation systems that we evaluated.

Table 1. Ventilation Systems Evaluated

Exhaust Ventilation Systems	**Components**
Upgraded bath exhaust	Quiet, efficient bathroom exhaust fan, with passive vents.
Single-port (SP) exhaust	Quiet, centrally located exhaust fan, with passive vents.
Multi-port (MP) exhaust	Remote exhaust fan ducted to bathrooms, with passive vents.
Supply Ventilation Systems	**Components**
Forced-air (FA) supply	Forced-air fan with permanent split capacitor (PSC) motor, outside-air duct with motorized damper.
ICM forced-air supply	Forced-air fan with variable-speed, integrated-control motor (ICM), outside-air duct with motorized damper.
Multi-port supply	Remote supply fan ducted to bedrooms and living areas.
Balanced Ventilation Systems	**Components**
Balanced heat-recovery	Heat-recovery ventilation unit ducted to and from rooms.
MP supply + SP exhaust	Remote supply fan ducted to bedrooms and living areas, and a quiet, centrally-located exhaust fan.
FA supply + SP exhaust	Forced-air fan with PSC motor, outside-air duct with motorized damper, and a quiet, centrally located exhaust fan.

[1] Fans located remotely need not be as quiet as those located near the living space.

Evaluation Criteria

The ENERGY STAR Homes program requires that ventilation systems be able to maintain indoor air quality in accordance with ASHRAE Standard 62-1989 (ASHRAE 1989). Also, because production builders seek to minimize equipment and labor costs, they require ventilation systems that are inexpensive and simple to install. In addition, because buyers of production homes have no input to design decisions that they will live with, we determined that ventilation systems recommended for ENERGY STAR homes should also minimize depressurization, be affordable to operate, distribute ventilation air effectively within the home, and avoid ventilation-related condensation in exterior walls.

Minimizing depressurization is a safety and health priority: negative indoor pressure as low as 3 Pascals can cause backdrafting (flue gas reversal) of fireplaces and combustion appliances, pull automobile exhaust from an attached garage, and introduce radon gas (if present) into a home through the foundation (Brook 1996; Wilber & Cheple 1997). Many newer homes can be temporarily depressurized during the operation of a kitchen range hood, clothes dryer, or forced-air system with net supply duct leakage, but because a ventilation system is supposed to *improve* air quality, it should be designed to alleviate – not exacerbate – depressurization. Therefore, the exhaust ventilation systems we evaluated include passive vents that allow air to flow through them in either direction to relieve indoor-outdoor pressure imbalances (Bower 1995). Unlike exhaust ventilation, supply ventilation creates a positive indoor pressure, which helps keep outdoor pollutants out of the home and also buffers against depressurization, which is less frequent, severe, or prolonged than without a supply fan. With a balanced ventilation system, indoor pressure fluctuates near neutral, which is preferable to negative indoor pressure, but not as beneficial as positive indoor pressure.

For residential ventilation to be effective, outdoor air must be distributed throughout the home, particularly to bedrooms, where (most) people spend most of their time (Reardon 1995). Exhaust ventilation works by removing indoor air, which is replaced by outdoor air entering through windows or other openings; effective distribution depends on the ability of air to circulate freely from each room to the exhaust fan. Supply ventilation works by introducing outdoor air, which pushes indoor air out through available openings; to be effective, supply ventilation air must be distributed to rooms via ductwork. Balanced ventilation distributes ventilation air most effectively, because it exhausts air from at least one location, and supplies air (via ductwork) to several rooms. Regardless of which type of ventilation system is used, indoor air must be able to circulate freely between rooms when interior doors are closed. Therefore, home builders should always use at least one of the following measures: (1) install forced-air returns in every bedroom, (2) install through-wall transfer grilles in every bedroom, and (3) verify (by measuring airflow) that interior doors are adequately undercut or louvered.

In some climates, indoor pressure can affect the long-term structural integrity of a house. Positive indoor pressure pushes indoor air out through exterior walls where, in very cold climates, any moisture it contains will condense on the first surface whose temperature is below dew point (for example, the inside surface of exterior sheathing). If a wall has a vapor barrier on the exterior surface, or if the heating season is prolonged, accumulation of moisture in the wall cavity may eventually cause wooden framing to rot. Similarly, negative indoor pressure pulls outdoor air into a home through exterior walls where, in hot humid climates, moisture will condense on the first cool (air-conditioned) surface within a wall (for example, the outside surface of the interior finish). If the interior surface of the wall is a vapor barrier, moisture in the wall cannot "dry to the inside," and accumulated condensation may lead to rot. Ventilation-related condensation in exterior walls is not a concern in arid climates or with balanced ventilation.

Methodology

In each climate, we modeled the nine ventilation systems in prototypical ENERGY STAR homes with two types of space conditioning equipment: (1) gas furnace with central air conditioner, and (2) electric heat pumps (except we did not evaluate heat pumps in Boston, where they are seldom used). For each equipment type and climate, we compared ventilation systems on the basis of (1) annualized capital cost, (2) annual operating cost, (3) potential depressurization, (4) effective distribution of ventilation air within a home, and (5) potential ventilation-related condensation within exterior walls.

Capital Costs

Installation cost estimates were based on information provided by manufacturers, distributors, *R.S. Means 1997 Mechanical Cost Data* (Means 1997) and a recent survey of contractors in New York and California.[2] They include materials, labor, and 25% builder's overhead and profit. We assumed that installation costs are the same in all locations, and that exhaust systems include six passive vents.

In addition to installation cost, ventilation capital costs include periodic replacement of system components. Our calculations of annualized capital costs were based on a 20-year ventilation system lifetime, a 7% real discount rate, and the following equipment replacement schedule:

- PSC (permanent split capacitor) forced-air fans used continuously require motor replacement every five years at a (motor) cost of $200,[3]
- Exhaust and supply ventilation fans require replacement after 10 years at a (fan) cost of $200, and
- Forced-air fans with ICMs (integrated-control motors) require replacement of controls after 10 years on average at a (controls) cost of $200 (Archer 1998).

Table 2 shows estimated ventilation capital costs. Systems are sorted by installation cost.

Table 2. Ventilation System Capital Costs

Ventilation System	Installation Cost ($)	Annualized Capital Cost ($)
Forced-air (FA) supply	300	73
Upgraded bath exhaust	463	57
Single-port (SP) exhaust	613	71
Multi-port (MP) supply	650	74
FA supply + SP exhaust	663	120
MP supply + SP exhaust	888	111
Multi-port exhaust	1,063	110
ICM forced-air supply	1,550	183
Balanced heat recovery	1,838	195

Operating Costs

The cost of operating a ventilation system includes the energy used by ventilation fan(s) as well as the cost of tempering ventilation air and any infiltration attributable to active ventilation; it does not include the cost of tempering air that would infiltrate the home in the absence of ventilation. We estimated ventilation operating costs by modeling and calculating system performance in several steps.

We selected one city and its Typical Meteorological Year weather data (Marion & Urban 1995) to represent each climate: Boston (cold), Washington DC (mixed), Houston (hot humid), and Phoenix (hot arid). We used an average of 1995 gas and electric prices from major utilities serving each city. Our prototypical homes had 2000 sq. ft. of conditioned space; those in Boston and Washington had

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[2] Synertech Systems Corp., Inc. conducted an unpublished survey of residential ventilation costs for LBNL, New York State Energy Research and Development Authority and the California Institute for Energy Efficiency.

[3] PSC forced-air fans have an estimated service life of about 10 years under normal duty (25–35% of 8760 hrs/yr) (GRI 1994). We estimate that service life will decrease by a factor of two if operating hours increase by a factor of three.

two stories with a basement, and those in Houston and Phoenix had one story with a slab foundation. By definition, ENERGY STAR homes earn a Home Energy Rating of at least 86 (of 100 possible) points on the (draft) national HERS Council rating scale (HERSC 1996).

We used RESVENT [4] to estimate heating and cooling loads attributable to active ventilation. We assumed that homes have 0.20 ACH average annual infiltration, that ventilation systems operate continuously (8,760 hrs/year) and deliver 0.35 average annual ACH, and that windows remain closed.[5]

Our operating cost estimates do not account for heat gain or loss of supply ventilation ducts, which we assumed to be well sealed and insulated and/or within conditioned space. More research is needed to quantify the impact of heat gains on ventilation ducts located in attics in hot climates. Attic heat gain of supply ventilation ducts should be *more* than that on forced-air ducts to the extent that forced-air conditioning is intermittent, while ventilation is continuous. On the other hand, attic heat gain on supply ventilation ducts should be *less* than that on forced-air ducts to the extent that (1) ventilation ducts are smaller than forced-air ducts (ventilation airflow is about 10% of forced-air flow), so ventilation ducts have much less surface area, (2) the difference in temperature between ventilation supply ducts and the attic is less than that of forced-air supply ducts because ventilation air is unconditioned outdoor air, while forced-air ducts contain cooled air, and (3) in the heating season, attic heat gain serves to temper ventilation supply air, thus reducing ventilation operating costs in winter.

In general, ventilation system operation should be automatic and continuous (i.e., non-stop). The exception is *Forced-air supply*, which depends on a standard PSC forced-air fan for ventilation; because high operating costs make continuous operation of these fans prohibitive, they should operate continually (i.e., automatically, at regular intervals) (Jackson 1993). Therefore, because our operating cost estimates are based on continuous operation, our operating cost estimates for *Forced-air supply* are higher than they would be if we assumed that *Forced-air supply* systems operated continually.

In each climate, we modeled the same home with each ventilation system, and with 0.20 ACH infiltration only. The load attributable to infiltration only was subtracted from the load attributable to ventilation *and* infiltration to determine the load attributable to ventilation only. However, ventilation affects the infiltration rate, so the effective air change rate is different for each climate and ventilation system. Therefore, before estimating operating costs, we normalized RESVENT heating and cooling loads attributable to ventilation to a total ventilation rate of 0.50 ACH (Feustel, Modera & Rosenfeld 1987).

For forced-air ventilation strategies, we used the DOE-2 building energy simulation program (Birdsall et al. 1990) to determine the annual operating hours per year for the forced-air fan for heating and cooling and, by subtraction (from 8,760 hours per year), for ventilation.

To estimate ventilation fan operating costs, we assumed a ventilation system static pressure of 0.25 w.g. for exhaust systems and 0.50 w.g. for supply (i.e., ducted) systems. We assumed that heat recovery (HRV) units consume 1.00 W/cfm, spot exhaust fans consume 0.60 W/cfm, PSC forced-air fans consume 0.50 W/cfm, PSC ventilation fans consume 0.30 W/cfm, and ICM forced-air fans consume 0.25 W/cfm.[6] We assumed that the ventilation airflow (in cfm) of *Forced-air supply* is 75% of the cooling airflow, and that ventilation airflow of *ICM forced-air supply* is 50% of cooling airflow.

Table 3 shows ventilation system operating costs in homes with electric heat pumps, and Table 4 shows ventilation system operating costs in homes with gas furnaces and central air-conditioning.

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[4] RESVENT is an hourly ventilation simulation computer program developed by the Indoor Environment Program at LBNL; it incorporates the Sherman-Grimsrud Method. The ASHRAE 136 method was used to determine normalized leakage areas corresponding to annual average infiltration rates of 0.20 ACH (ASHRAE 1993).

[5] Reasons that people keep their windows closed year-round include security, noise, asthma, allergy, infirmity, outdoor air pollution, and outdoor humidity. We assumed that windows remained closed in order to model this not uncommon scenario, and to account for the interaction of infiltration and mechanical ventilation in our operating costs. Furthermore, because we assumed ventilation is continuous, open windows would not affect our ventilation operating costs.

[6] We used W/cfm rates based on measured data if available, and manufacturer literature, if not. PSC and ICM forced-air fan W/cfm rates are based on measured data from a few existing FL homes and was provided by Danny Parker of the Florida Solar Energy Center; ventilation fan W/cfm rates are based on product literature from fan manufacturers.

Table 3. Ventilation System Annual Operating Costs in Homes with Electric Heat Pumps
Systems are sorted by Total Annual Operating Cost.

Washington DC	Fan(s)	Heating	Cooling	Total
Balanced heat recovery	$107	$0	$0	$107
Multi-port supply	$31	$111	$23	$165
Multi-port exhaust	$27	$124	$24	$176
Single-port exhaust	$28	$128	$25	$181
Upgraded bath exhaust	$28	$129	$25	$183
MP supply + SP exhaust	$34	$146	$25	$205
ICM forced-air supply	$118	$111	$23	$252
Forced-air supply	$349	$111	$23	$483
FA supply + SP exhaust	$365	$146	$25	$536
Houston	**Fan(s)**	**Heating**	**Cooling**	**Total**
Balanced heat recovery	$120	$0	$0	$120
Multi-port supply	$29	$43	$91	$163
Upgraded bath exhaust	$27	$45	$95	$167
Multi-port exhaust	$27	$45	$96	$168
Single-port exhaust	$27	$46	$95	$168
MP supply + SP exhaust	$38	$48	$98	$183
ICM forced-air supply	$123	$43	$91	$256
Forced-air supply	$364	$43	$91	$498
FA supply + SP exhaust	$382	$48	$98	$528
Phoenix	**Fan(s)**	**Heating**	**Cooling**	**Total**
Balanced heat recovery	$118	$0	$0	$118
Multi-port supply	$28	$45	$70	$143
Multi-port exhaust	$26	$45	$74	$144
Upgraded bath exhaust	$26	$46	$74	$146
Single-port exhaust	$27	$47	$75	$148
MP supply + SP exhaust	$37	$48	$82	$166
ICM forced-air supply	$172	$45	$70	$286
Forced-air supply	$512	$45	$70	$626
FA supply + SP exhaust	$530	$48	$82	$659

Table 4. Ventilation System Annual Operating Costs in Homes with Gas Furnace/AC
Systems are sorted by Total Annual Operating Cost

Boston	**Fan(s)**	**Heating**	**Cooling**	**Total**
Balanced heat recovery	$149	$0	$0	$149
Multi-port supply	$40	$127	$18	$185
Multi-port exhaust	$36	$141	$19	$197
Single-port exhaust	$37	$142	$19	$197
Upgraded bath exhaust	$37	$143	$19	$199
MP supply + SP exhaust	$47	$157	$19	$224
ICM forced-air supply	$158	$127	$18	$303
Forced-air supply	$469	$127	$18	$614
FA supply + SP exhaust	$491	$157	$19	$668
Washington DC	**Fan(s)**	**Heating**	**Cooling**	**Total**
Balanced heat recovery	$107	$0	$0	$107
Multi-port supply	$31	$73	$23	$127
Multi-port exhaust	$27	$82	$24	$134
Single-port exhaust	$28	$84	$25	$137
Upgraded bath exhaust	$28	$85	$25	$139
MP supply + SP exhaust	$34	$96	$25	$155
ICM forced-air supply	$122	$73	$23	$218
Forced-air supply	$362	$73	$23	$458
FA supply + SP exhaust	$377	$96	$25	$499
Houston	**Fan(s)**	**Heating**	**Cooling**	**Total**
Balanced heat recovery	$120	$0	$0	$120
Multi-port supply	$29	$33	$91	$153
Upgraded bath exhaust	$27	$35	$95	$157
Single-port exhaust	$27	$36	$95	$158
Multi-port exhaust	$27	$35	$96	$158
MP supply + SP exhaust	$38	$37	$98	$173
ICM forced-air supply	$121	$33	$91	$245
Forced-air supply	$359	$33	$91	$484
FA supply + SP exhaust	$377	$37	$98	$512
Phoenix	**Fan(s)**	**Heating**	**Cooling**	**Total**
Balanced heat recovery	$118	$0	$0	$118
Multi-port supply	$28	$40	$70	$138
Multi-port exhaust	$26	$40	$74	$140
Upgraded bath exhaust	$26	$41	$74	$142
Single-port exhaust	$27	$42	$75	$144
MP supply + SP exhaust	$37	$43	$82	$162
ICM forced-air supply	$167	$40	$70	$277
Forced-air supply	$497	$40	$70	$607
FA supply + SP exhaust	$514	$43	$82	$639

Evaluation

In order to compare ventilation systems for homes with each type of equipment in each climate, we assigned relative scores to each system for each of the cost and effectiveness criteria. Individual scores were totaled and used to rank systems for overall cost and effectiveness.

Table 5 presents our method of assigning relative scores. We weighted the criteria equally.

Table 6 shows the total scores and overall ranking of ventilation systems for each climate.

Table 5. Scoring Method

Score	Annualized Capital Cost	Score	Annual Operating Cost
3	$ 50–75	3	$100–150
2	76–100	2	151–200
1	101–125	1	201–250
0	126–150	0	251–300
-1	151–175	-1	301–350
-2	176–200	-2	351–400
-3	> 200	-3	> 400

Score	Distribution of Ventilation Air within the home
3	Air is supplied (ducted) to and exhausted from several locations.
2	Air is supplied (ducted) to several rooms and exhausted centrally.
1	Air is supplied (ducted) to several rooms.
-1	Air is exhausted from several rooms.
-2	Air is exhausted from a central location.
-3	Air is exhausted from one bath.

Score	Potential for Depressurization
3	Positive indoor pressure (supply systems)
0	Near-neutral pressure (balanced, or exhaust with passive vents)
-3	Negative indoor pressure (exhaust w/o vents, none evaluated)

Score	Potential for Condensation in Exterior Walls
3	Indoor pressure prevents condensation.
0	Indoor pressure is neutral, or there is no potential problem.
-3	Indoor pressure can cause condensation.

Of course, any other numeric scale could be used, criteria could be weighted, and different or additional criteria (e.g., the ability to filter ventilation air) could be used. We encourage practitioners to use their own scale, criteria and weights to evaluate these and other residential ventilation systems.

Results

Table 6. Overall Cost and Effectiveness of Ventilation Systems

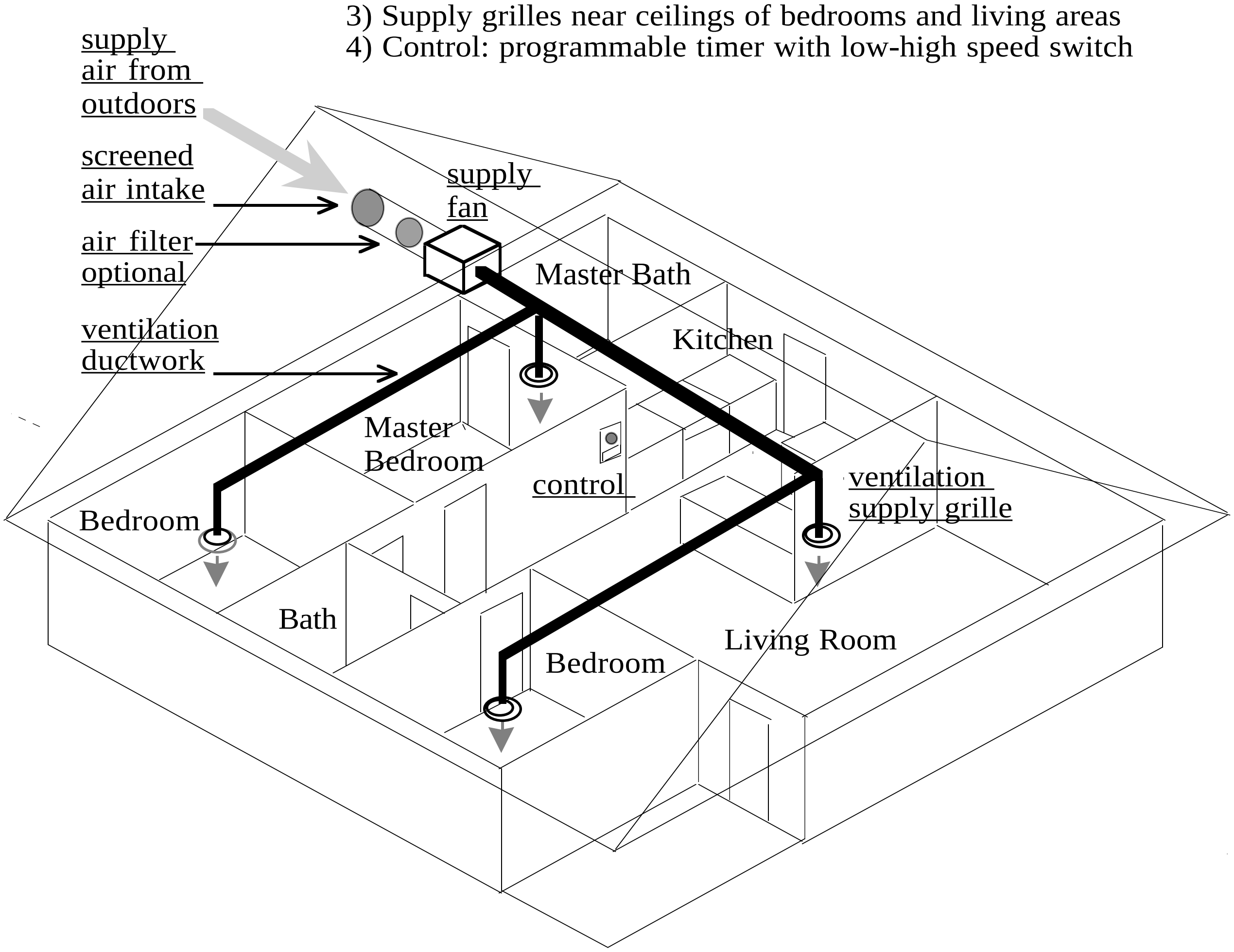
Systems are sorted by Total Score.	**Homes with Gas Furnace, Central Air Conditioning**		**Homes with Heat Pumps**	
BOSTON	Total Score	Overall Rank		
Multi-port supply	5	1		
MP supply + SP exhaust	4	2		
Balanced heat recovery	3	3		
Single-port exhaust	3	3		
Multi-port exhaust	2	4		
Upgraded bath exhaust	2	4		
Forced-air supply	0	5		
FA supply + SP exhaust	-1	6		
ICM forced air supply	-2	7		
WASHINGTON DC	Total Score	Overall Rank	Total Score	Overall Rank
Multi-port supply	9	1	8	1
MP supply + SP exhaust	5	2	4	2
Single-port exhaust	4	3	3	3
Balanced heat recovery	3	4	3	3
Forced-air supply	3	4	3	3
Multi-port exhaust	3	4	2	4
Upgraded bath exhaust	3	4	2	4
ICM forced air supply	2	5	2	4
FA supply + SP exhaust	-1	6	0	5
HOUSTON	Total Score	Overall Rank	Total Score	Overall Rank
Multi-port supply	11	1	11	1
Forced-air supply	6	2	6	2
ICM forced air supply	6	2	5	3
MP supply + SP exhaust	5	3	5	3
Balanced heat recovery	3	4	5	3
Single-port exhaust	3	4	3	4
Multi-port exhaust	3	4	2	5
Upgraded bath exhaust	2	5	2	5
FA supply + SP exhaust	-1	6	-1	6
PHOENIX	Total Score	Overall Rank	Total Score	Overall Rank
Multi-port supply	9	1	9	1
MP supply + SP exhaust	5	2	5	2
Single-port exhaust	4	3	4	3
Balanced heat recovery	3	4	3	4
Forced-air supply	3	4	3	4
Multi-port exhaust	3	4	3	4
Upgraded bath exhaust	3	4	3	4
ICM forced air supply	2	5	2	5
FA supply + SP exhaust	-1	6	-1	6

Figure 1. Multi-Port Supply Ventilation

Ventilation equipment size is exaggerated for clarity.

Multi-port Supply System Components:

1) Quiet, efficient supply fan with air screen and filter.
2) Ventilation ductwork located within conditioned space.
3) Supply grilles near ceilings of bedrooms and living areas
4) Control: programmable timer with low-high speed switch



Multi-port Supply Ventilation Operation:

1) The supply fan operates continuously on low speed.
2) Spot fans exhaust air from kitchen and bathrooms.
3) Residents can temporarily boost the ventilation rate.

Conclusions

Table 6 shows that *Multi-port supply* ventilation scores highest in all climates with both types of heating and cooling equipment; furthermore, except in Boston, *Multi-port supply* scores almost twice as high as any other system. Therefore, we recommend *Multi-port supply* ventilation for tight production homes in mixed, hot humid, and hot arid climates. However, because attic heat gain may significantly impact the tempering portion of operating costs, we recommend that *Multi-port supply* ductwork be located within conditioned space. Figure 1 illustrates *Multi-port supply* ventilation.

In cold climates, where supply ventilation can cause moisture problems in exterior walls, we recommend the balanced system *Multi-port supply* + *Single-port exhaust*. During the heating season, both fans should be operated for balanced ventilation, but between heating seasons, residents have the option of using both fans for balanced ventilation, or using the supply fan alone (i.e., *Multi-port supply*), in which case they benefit (during part of the year) from positive indoor pressure and lower operating costs. Also, because heat recovery greatly reduces ventilation operating costs, we suggest production builders offer *Balanced heat recovery* ventilation systems to buyers as an optional upgrade.

For builders who prefer to install *Forced-air supply* instead of *Multi-port supply* ventilation, we strongly recommend that forced-air ducts be within conditioned space, and that the forced-air fan be automatically operated for at least 10 minutes per hour. Also, because ICM fans significantly reduce operating costs, we suggest builders offer ICM forced-air fans to buyers as an optional upgrade.

Table 7 summarizes our recommendations.

Table 7. Summary of Ventilation Recommendations

Cold Climate	**Caveats**
Multi-port supply + Single-port exhaust	No caveats.
Forced-air supply + Single-port exhaust	Install ductwork within conditioned space.
	Install control to operate fan 10–15 min each hour.
	Offer buyers the option of upgrading to an ICM fan.
Balanced heat recovery	Offer buyers the option of upgrading to an HRV.
Mixed, Hot Arid, Hot Humid Climates	**Caveats**
Multi-port supply	Install ductwork within conditioned space.
Forced-air supply	Install ductwork within conditioned space.
	Install control to operate fan 10–15 min each hour.
ICM forced-air supply	Offer buyers the option of upgrading to an ICM fan.

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