OPTIMUM VENTILATION AND AIR FLOW CONTROL IN BUILDINGS

17th AIVC Conference, Gothenburg, Sweden

The Evolution of Ventilation in Manufactured Housing in The Northwestern United States

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Synopsis:

Electric utilities in the Pacific Northwest have spent over $100 million to support energy efficiency improvements in the HUD-code manufactured housing industry in the Pacific Northwest over the past several years. Over 65,000 manufactured housing units have been built since 1991 that exceed the new HUD standards for both thermal performance and mechanical ventilation that became effective in October, 1994. All of these units included mechanical ventilation systems that were designed to meet or exceed the requirements of ASHRAE Standard 62-1989. This paper addresses the ventilation solutions that were developed and compares the comfort and energy considerations of the various strategies that have evolved in the Pacific Northwest and nationally. The use and location of a variety of outside air inlets will be addressed, as will the acceptance by the occupants of the ventilation strategy.

Key words/terminologies

BPA -- Bonneville Power Adminstration, a United States Department of Energy power marketing agency in the Pacific Northwest

DAPIA -- Design Approval Primary Inspection Agency -- Technical agency which reviews manufacturer designs to determine compliance with FMHCSS

FMHCSS -- Federal Manufactured Home Construction and Safety Standards -- Federal safety and performance standards for manufactured homes

IPIA- - In-Plant Primary Inspection Agency -- Inspect home construction process (in factory) to ensure compliance with DAPIA-approved designs

RCDP -- Residential Construction Demonstration Program -- Research and demonstration program funded by the Bonneville Power Adminstration and operated by the state energy offices in the Pacfic Northwest

Spot ventilation -- Removal of air from bathrooms and kitchens during bathing and cooking.

Ventilation effectiveness (temporal) -- Time-weighted ventilation: getting the ventilation to the occupants when they need it.

Ventilation effectiveness (spatial) -- Zone-weighted ventilation; getting ventilation to zone(s) occupants occupy.

Whole house ventilation -- Devices designed to provide fresh air to all home zones and remove stale indoor air from these zones.

Introduction

Pacific Northwest electric utilities have invested over $100 million to improve energy efficiency in HUD-code manufactured housing. Over 65,000 manufactured homes have been built which exceed the 1994 Federal Manufactured Housing Construction Safety Standard (FMHCSS) thermal requirements and which rely on mechanical ventilation systems similar to those required by the 1994 FMHCSS. Research projects have analyzed ventilation system performance, energy costs, and occupant acceptance of various systems. These data have been used to develop ventilation approaches that meet the needs of both the housing manufacturers and the occupants.

The paper describes the evolution of manufactured home ventilation systems in the Pacific Northwest. System hardware is discussed, as are controls, occupant comfort, and operation issues. Performance of ventilation systems included in recently constructed homes is reported. The 1994 FMHCSS ventilation requirements use some of the information developed in the Pacific Northwest, but may still fail to meet ASHRAE Standard 62-1989. The research results include discussion of whole house air leakage, exhaust fan performance, HVAC system and building envelope interactions, and occupants' acceptance and operation of ventilation systems.

HUD-Code Housing Background

Manufactured housing is constructed on permanently affixed metal frames in factories, and shipped on wheels to sites where they are set up as single or multiple section units. The technology evolved out of World War II, combining cheap and plentiful surplus steel frames with the inexpensive, yet functional, interior design found in boat interiors. Mobile homes grew in size, features, and popularity throughout the '60s and '70s. Currently, manufactured homes comprise about 10% of all single family housing in the U. S. (Krigger 1994). In parts of the rural U. S., manufactured homes account for over 50% of single-family housing.

Prior to 1976, manufactured homes were more commonly referred to as "mobile homes" or "trailers" and were often built with minimal insulation and low-cost HVAC systems and provided low ($<\$20/ft^2$) first-cost new housing. Insulation and safety standards for these homes were codified primarily in the Uniform Building Code (UBC) and various ANSI standards. In 1974, in response to growing concern that the industry be regulated by a single body, Congress enacted the National Manufactured Housing Construction and Safety Standards Act. Two years later, HUD adopted national industry building standards known as the Federal Manufactured Housing Construction and Safety Standards (FMHCSS) and became the regulator of the industry. Day-to-day regulation of the industry is carried out with the cooperation of state inspection agencies which are under supervision by HUD's technical contractor, the National Conference of States on Building Codes and Standards (NCS/BCS).

In 1994, the FMHCSS thermal and ventilation requirements were updated at the request of Congress. A national research laboratory developed revisions to thermal standards, which they estimated would provide about $300 million in annual national energy savings to new homebuyers over current practice, and about $400 million compared to the 1976 FMHCSS. (Conner et al., 1992)

Infiltration-induced heating and cooling were estimated to account for approximately 20% to 30% of the total load in a typical manufactured home. The lab analysis did not attempt to evaluate energy conservation measures that would lower infiltration rates. Thus no changes were made in the 1994 FMHCSS for infiltration control options. This decision was based on several assumptions:

1. No requirement was clearly present in the enabling federal legislation to include additional infiltration reduction measures in the 1994 FMHCSS.
2. New manufactured homes were relatively airtight, so very low natural infiltration rates would result from further tightening. HUD has estimated the average natural infiltration rate in new manufactured housing to be 0.25 air changes per hour (ACH). Various studies of airtightness in Pacific Northwest homes (reported later in this paper) confirm that newer manufactured homes are indeed built to this level of airtightness.
3. In the absence of mechanical ventilation, very low infiltration rates can have significant impacts on occupant health. A ventilation standard was not proposed in the national lab's recommendations because "standards to mitigate health effects of very low levels of infiltration are difficult based on the current state-of-the-art, and would require further study." (Conner et al., 1992). There were also the practical concerns of specifying a target infiltration rate and assigning responsibility in the event of noncompliance. Manufacturers have no direct control over the home's site set-up. Inadequate structural support or air-sealing can increase infiltration levels significantly, especially at the marriage line between halves of a double-wide unit. Occupant control of mechanical ventilation systems is also a major determinant of ventilation effectiveness.

Ventilation effectiveness is more concerned with pollutant removal from the home rather than just the time-weighted average rate of building infiltration. Depending on the rate of natural infiltration, the interactions of the natural and mechanical ventilation, and the duty cycle of the mechanical ventilation system, the average ventilation rate and effective ventilation rate may be very different. The lab study suggested that "Although there is significant potential energy savings associated with reduced infiltration, this recommendation must be accompanied by ventilation measures that mitigate potential IAQ problems." (Conner et al. 1992) It further says "A reduction in infiltration levels should be accompanied by:

1. A clear definition of the minimum ventilation/infiltration rates required for occupant health and moisture control.
2. A practical and economical method for determining the maximum ventilation/infiltration rate and minimum ventilation/infiltration rate in commercially produced homes.
3. A clear definition of the ventilation characteristics other than rates (such as ventilation control and distribution) required to assure a healthy environment in a low infiltration home." (Conner et al., 1992)

Based on recommendations from National Institue of Standards and Technology (NIST) and their consultants (TenWolde and Burch, 1993), HUD ultimately decided to require that occupant-controlled, whole house, mechanical ventilation systems be installed, without requiring any additional airtightening measures beyond the 1976 FMHCSS.

FMHCSS Ventilation Requirements

The FMHCSS ventilation requirements include short-term spot ventilation specifications and whole house volumetric and distribution specifications.

Bath Spot Ventilation

The 1976 FMHCSS required bathrooms to have minimum size operable windows (1.5 ft^2) or mechanical "spot" ventilation using bathroom exhaust fans. This gave occupants the ability to exhaust indoor pollutants, such as moisture generated during bathing, by opening a window and/or switching on the bath fan. In 1994, the FMHCSS began requiring mechanical bathroom fans for spot ventilation in rooms with tubs or showers, but still allows only an operable window to ventilate toilet compartments.

Kitchen Spot Ventilation

The 1976 FMHCSS required kitchen spot ventilation to exhaust indoor air pollutants created during cooking, such as moisture and combustion by-products. Requirements included one of the following:

Kitchen range hoods

or

Passive stack ventilation with 12.5 square inches of area within 10 feet of the range

or

An operable window within 10 feet of the range

In 1994, the FMHCSS eliminated the use of operable windows to satisfy kitchen range spot ventilation requirements. Kitchen fans in the HUD homes required 90 CFM (42 L/s) installed capacity. Standard industry range hoods were installed which either exhaust through the roof (similar to the bath fan) or exhaust directly through an adjacent exterior wall. These fans have backdraft dampers installed.

Whole House Ventilation (1976 FMHCSS)

Whole house ventilation is designed to dilute and remove indoor pollutants which may not be associated with cooking and bathroom use. The 1976 FMHCSS required a home to have either 4% of floor area in operable windows or mechanical ventilation installed to provide "whole house" ventilation. Many manufacturers built 1976 FMHCSS homes using systems sold by the furnace manufacturers that integrate ventilation into furnace operation by using a fresh air duct from the outside to the furnace. These systems had the potential to pressurize the home and drive moisture into the attic, causing condensation.

Similar systems also sold by furnace manufacturers are commonly used by manufacturers to provide both whole house ventilation and mechanical attic ventilation. These systems introduce outside air into the homes interior and the attic cavity. A high-volume fan (about 300 CFM or 142 L/s) pushes air through the attic cavity and out attic vents. In newer homes with predominantly vaulted ceilings and hence limited free volume in the ceiling assembly, the usefulness of these fans may need further investigation.

Whole House Ventilation (1994 FMHCSS)
The 1994 FMHCSS ventilation standards require a mechanical occupant-controlled ventilation system. The system cannot be a dual spot/whole house fan located in the bathroom because of HUD's concern that spot ventilators are not designed for long duty cycles. The new requirements also specify that the occupant must be able to control the system with an accessible on/off control, and that the ventilation system must not create a net positive or negative pressure across the building envelope, in an effort to minimize envelope structure damage from elevated moisture levels.

The revisions in the FMHCSS ventilation requirements were an attempt by HUD to improve both temporal and spatial ventilation effectiveness in manufactured homes. A good faith effort was made to adopt some of the ventilation system ideas used in the Pacific Northwest, followed by a consensus and rule making process. These processes often result in requirements which may not accomplish all the original intent. The FMHCSS ventilation requirements do not address fan noise level, operating cycle, or specific thresholds of pressurization to avoid. The final FMHCSS requirements should improve ventilation in manufactured housing to the extent they are correctly designed and installed by the housing manufacturer and are used by occupants as intended. However, the lack of specificity in these requirements has raised considerable debate in the Pacific Northwest. Some of this debate is recounted in the discussion section of this paper.

BPA Ventilation System Specifications

BPA's specifications were designed to ensure adequate spot and whole house ventilation. A variety of whole house systems were authorized by BPA. By far the most common system installed in the early SGC and MAP manufactured homes was the integrated spot/whole house option based on two nominal 50 CFM (24 L/s) bathroom fans controlled by 24-hour timers.

Bath fans in most Pacific Northwest manufactured homes built to the 1976 FMHCSS were generally supplied by one manufacturer as a ceiling-mounted fan. The bathroom exhaust air was ducted to the vicinity of a roof jack or connected directly to an exhaust termination fitting provided by the fan manufacturer as a package with the bath fan. The bath fans had a plastic sponge-type backdraft damper which opens when the exhaust fan operates, and which tend to leak air when the bath fan is not operating. These backdraft dampers also tended to disintegrate and be blown away over time. When they fail, these devices often become seven inch passive stack ventilators.

Until changes in the FMHCSS caused manufacturers to consider improved fan products, the fans installed for dual duty (spot and whole house ventilation) were very inexpensive units which were not necessarily intended for long periods of daily use. This fact is important to remember when considering the long-term effectiveness of this ventilation system.

Kitchen spot ventilators were required to deliver 90 CFM (42 L/s) and were ducted either vertically or horizontally. Kitchen ventilators are not a primary focus of this discussion.

BPA-certified ventilation systems are required to meet both volumetric specifications and distribution specifications. The National Environmental Protection Act (NEPA) requires federal agencies to conduct an environmental impact statement (EIS) and ensure "findings of no significant impact" associated with actions or programs that could cause indoor air quality problems. BPA conducted a series of studies under the EIS process which resulted in requirements that mechanical whole house ventilation systems be installed in any homes involved with BPA programs. These programs have indeed resulted in construction of more air-tight homes.

The BPA whole house ventilation specifications were designed to provide for introduction of outdoor air to occupied zones (primarily bedrooms) in accordance with ASHRAE Standard 62-1989 and exhaust of stale indoor air to attain the seasonal average ventilation rate specified by Standard 62 (the greater of 0.35 ACH or 15 cfm or 7 L/s per person).

The problem with standards is that they are simplifications of a more complex interaction between building tightness, occupancy effects, and ventilation system effectiveness. Many indoor pollutants are associated with the level of occupancy. For CO_2 levels or biocontaminants that transmit disease from one person to another, ventilation systems should be governed by the number of occupants in a building. Relative humidity levels also correlate with occupancy level as more occupants bathe, cook, wash and emit water vapor. In the RCDP home occupant and site survey analysis (Palmiter et al., 1992), the volume of the building has little or no correlation with the number of occupants living there. The size of the home tends to be strongly correlated with family income but only weakly correlated with the number of occupants.

Under a volume-based specification, a very large home with two occupants must be ventilated at a higher level than a small manufactured home with four occupants. Although the intent of the specifications is to ensure 0.35 ACH, the SGC and MAP specifications are not directly based on volume. Instead, they are based on the number of bedrooms in the home, which is more closely correlated with number of occupants. BPA requires a whole house mechanical ventilation system with a measured installed capacity of providing 45-90 CFM (21-42 L/s) in 1-4 bedroom homes, respectively, as shown in Table 1. An additional 15 cfm (7 L/s) beyond the normal ASHRAE 62 level is specified for the main living area because of high occupant levels.

Table 1
SGC/MAP Performance Specifications for Whole House Ventilation

# Bedrooms	Measured Flow
1	45 CFM (21 L/s)
2	60 CFM (28 L/s)
3	75 CFM (35 L/s)
4	90 CFM (42 L/s)

To ensure a minimum exhaust capacity exists for bathroom spot ventilation (50 CFM or 24 L/s) and whole house fans, system flow rate testing is provided by staff from the state energy offices to manufacturers whenever any design changes are made to the spot and/or whole house fans, ductwork or exhaust termination devices. Manufacturers use small flow hoods provided by state energy offices to test flow rates and determine if they comply with the performance specification flow rates as part of the design and commissioning process.

A maximum noise rating of 1.5 sones is required on all whole house exhaust fans. This is reduced to 1.0 sone for fans operating continuously. Sone ratings were specified in hopes that occupants would operate bath fans for whole house ventilation on a duty cycle of sufficient length to actually increase the effective ventilation rate of the home. This was born out in a recnet survey by the Washington State Energy Office of 50 MAP home owners. The systems used by Pacific Northwest manufacturers in 1995 are summarized in Table 3 and described in more detail below.

Table 2
Ventilation Systems used by Pacific Northwest Manufacturers in 1995 to meet MAP ventilation specifications

System Type	Number of Manufacturers	% of Manufacturers
(1) Combination bath/whole house fan	7	33%
1.5 sone		
Window inlet vents		
24-hour timer control		
(2) Dedicated whole house fan	8	38%
Continuous operation		
0.5-1.0 sone		
Window inlet vents		
On-off switch control of whole house fan*		
(3) Dedicated whole house fan	1	5%
Intermittent operation		
1.5 sone		
Outside air to furnace		
Timer controls furnace and whole house fan		
(4) Dedicated whole house fan	3	14%
Continuous operation		
0.5-1.0 sone		
Outside air to furnace		
On-off switch control of whole house fan		
(5) Balanced flow HRV system	2	10%
Connected to furnace		
Timer control of HRV system		
Total =	21	100%

* One of these uses a timer instead of on-off switch
Options 2-5 also require spot ventilation fans in the bathrooms

Combination Spot/Whole House & Dedicated Whole House Exhaust (Systems 1 & 2)
The most common ventilation systems employed in these manufactured homes under the SGC program were (1) combination bathroom and whole house exhaust fans and (2) dedicated whole house fans. These systems are designed to provide general ventilation at least during periods of occupancy. The combination system provides the bathroom "spot" ventilation needs of occupants when using the bathroom, with whole house ventilation provided via operation of a 24-hour timer. Fresh air inlet vents are supposed to provide the necessary fresh air in each bedroom and in the main living space (even though the performance of these vents , as currently sized, probably adds little additional ventilation to the home, as discussed below.)
This system ran afoul of the 1994 FMHCSS because it relied on a spot ventilator for whole house ventilation. HUD's issue was the use of inexpensive bath fans, but the FMHCSS mandated that the whole house fan could not be located in the bathroom. Many manufacturers switched to a dedicated, continuous fan for whole house ventilation when the federal specifications changed. By doing this, they also met MAP specifications.

The dedicated system cannot be located in a bathroom and must use a separate ventilator for whole house ventilation. Generally the dedicated whole house fan is located in a hallway, operates continuously, is rated at 1.0 sone or less, and uses an on-off switch rather than a 24-hour timer to secure the fan during periods of long vacancy. The 0.5 and 1.0 sone exhaust fans typically use 15-17 watts to run the fan motor, which is considerably less than the 1.5 sone combination fans' typical 60-75 watts. On an annual basis, the parasitic energy cost of the quieter continuously-operating fan is less than $10 in most Pacific Northwest locations. This dedicated fan is also of considerably higher quality than most bath fans and therefore expected to last much longer.

Furnace-Based Systems (Systems 3 & 4)
Some manufacturers use an outside air intake system running from the roof to inside the furnace cabinet. This duct supplies outside air which is distributed by the furnace fan. In newer systems, a timer on the furnace fan allows for occupant- controlled ventilation independent of the furnace thermostat. While these systems reduce construction costs by eliminating need for passive air inlet window vents, they rely on the furnace fan (generally drawing at least 350 watts), to distribute air, consuming significantly more parasitic energy than fan/air inlet systems. No evaluation of the newer furnace based systems that ventilate independently of the thermostat has been conducted.

Several of the manufacturers have used "flapper dampers" to relieve possible pressure differentials caused by the operation of furnace-based ventilation. The 1994 FMHCSS require the use of a device to relive this pressure, but give no standards for what level of pressurization is acceptable and what size the damper needs to be. More research is needed in this area.

Balanced Flow Systems (System 5)
A few manufacturers have tried an innovative balanced flow system which preheats outside air to the furnace with exhaust air using a heat recovery ventilator (HRV) core and fan. These systems are attractive since they are designed to integrate into the furnace ductwork but work independently from the furnace operation. They do not cause pressure imbalances like other

systems and they provide some heat recovery and tempering of outside air. Evaluation of field installations of this system has been limited and most manufacturers have dropped this approach.

Through-the-wall HRVs which are designed to provide ventilation independent of the furnace ductwork are not approved for the BPA program unless units are installed in the main living area and each bedroom (to meet fresh air distribution requirements). It is unclear if an HRV installed in one zone of the home can provide adequate spatial ventilation effectiveness.

Air Inlet Vents

Air inlet vents as employed in the Pacific Northwest were designed to improve the distribution of outdoor air to occupants if a furnace-based distribution system is not used. Window sash vents or through-the-wall vents are installed in each bedroom and in the main living area. These vents are designed to provide small amounts of outdoor air to bedrooms and living zones to improve the ventilation of the living zones typically occupied. Occupants are instructed to leave these vents open and to only close them for brief periods when cold drafts or dust storms are encountered.

Outdoor air intake occurs whenever a negative building envelope pressure exists. Manufactured homes commonly are depressurized slightly (0.5 to 1.5 Pa) when interior fans operate. Tests run on window inlet vents in laboratory settings have achieved air flows close to that recommended by ASHRAE Standard 62 (15 CFM (7 L/s) per bedroom), but only at pressure differentials far above those commonly encountered across exterior bedroom walls; that is, the test had to be conducted at 15-20 Pa (depending on the mesh size of aluminum screens installed with these vents) to produce air flow of 15 CFM (7 L/s).

One of the authors has conducted tracer gas measurements of air flow through a window vent installed in a typical MAP home bedroom (Davis, 1996). The vent measures roughly 1/2" by 14", and has a net free venting area estimated at 2 in^2 (Luoma et al., 1988). With two exhaust fans running (combined exhaust flow of 110 CFM (52 L/s)) and the interior bedroom door closed, air flow into the bedroom increased by 3.65 ±0.16 CFM (1.72 +/-0.076 L/s). The test was conducted with a single tracer gas and therefore does not estimate the amount of air entering the room through interior wall penetrations. Another study (Palmiter et al., 1996), which measured ventilation in new Pacific Northwest multifamily buildings, found the vents admitted an average of 3.1 CFM (1.46 L/s) of outside air when the building was subjected to negative pressures resulting from exhaust fan operation. This study utilized a multi-zone tracer gas injector/sampler designed by Lawrence Berkeley Laboratory which has been used in a number of ventilation research projects in the Northwest.

In summary, the window vents do admit some amount of outside air into homes when they are open and fans operate; however, flows through these vents (as currently sized) are very modest

Cost Comparison of Whole House Ventilation Systems Used to Meet 1994 FMHCSS

Analysis of annual operating costs of the systems which can be used to meet the 1994 FMHCSS reveals a dramatic difference between the two most common whole house ventilation systems currently installed in Pacific Northwest manufactured homes: continuous exhaust-only systems and intermittent furnace-based systems.

The systems are compared on the basis of their ability to ventilate an identical double-section home to an effective ventilation rate of 0.35 ACH. Air at standard density is used in the calculation, along with TMY weather data for the sites mentioned. The analysis is done for electric heat. It assumes no extra energy penalty for duct losses. If such losses were included, which can be quite large and are difficult to calculate, the furnace-based system would be even more costly. The furnace-based system is assumed to use a 375 watt air handler fan to distribute outside air and an exhaust fan rated at 70 CFM (33 L/s) at 0.1" W.G. (and drawing 84 watts) to exhaust stale indoor air. Partial credit is given to the furnace-based system for addition of fan motor heat energy to the incoming fresh-air stream. The exhaust-only system uses a 0.5 sone exhaust fan rated at 70 CFM (33 L/s) at 0.10" W.G. and drawing only 14 watts.

Table 3
Cost Comparison of Most Popular Ventlation Systems in the Pacific Nrothwest
(Seattle TMY weather)

System	Annual energy to run system (kWh)	Annual heating energy for introduced ventilation air	Annual total cost (assuming $0.08/kWh)
Continuous exhaust fan	112	1213	$106
Furnace-based system	2848	835	$295

The furnace-based system must be interlocked with an adequate exhaust fan and run approximately 17 hours a day even during times of the year when heating or cooling may not be required to meet the ASHRAE Standard 62 recommended ventilation level of 0.35 ACH. Parasitic energy costs from using a furnace air handler fan to circulate outside air are significant. Comfort concerns are also significant, depending on where the home is sited. In practical terms, it is unlikelythat many homeowners will use such a system for maintaining indoor air quality.

Conclusions

Summary

Manufactured home ventilation systems can supply effective ventilation on a whole house basis, but only if the system is designed so that occupants will use it. Systems that achieve the intended installed capacity and are "user friendly" enough in terms of noise, drafts, and controls will encourage homeowner acceptance.

Results from the Pacific Northwest indicate past attempts at mechanically ventilating new manufactured homes have not succeeded in meeting ASHRAE Standard 62. Systems based on intermittent operation are sized adequately, but run times are short (generally less than 4 hours per day for each fan), so that combined natural and mechanical ventilation rates are still modest. Newer systems designed to run continuously with minimal fan operation costs may prove more successful in raising effective ventilation rates.

Since environmental effects from indoor air pollutants are not well understood by most home occupants, it is likely that many people will not perceive the need to operate ventilation systems very frequently. If the high failure rate in meeting ASHRAE Standard 62 in newer manufactured homes is viewed as a problem, more work should be done to investigate improvements to ventilation systems in these homes.

For more discussion of the current research and an extended version of this paper, see "Mechanical Ventilation in HUD-Code Manufactured Housing in the Pacific Northwest" to be presented by the authors at the 1997 ASHRAE Winter meeting, Philadelphia, PA, January, 1997

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