Design Guidelines For Combustion Air Systems

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Fuel-burning appliances require air for combustion. When the appliances are located in enclosed spaces, provision must be made for supplying the required amounts of air. Depending on the specifics of the appliances and the enclosure, additional air may be required for draft hood dilution and space conditioning. An enclosed space can be a mechanical room in a building, a furnace room in a residence or the entire floor of a building if a separate enclosure is not used to isolate the combustion appliance(s). An example of the latter is an unenclosed warm-air furnace in a basement of a residence.

Although no universally accepted rules exist for the supply of air to enclosed spaces, failure to supply adequate air may result in erratic or even dangerous operating conditions. Additional problems may arise in cold climates where excess ventilation of the space may occur, lowering the interior temperature to the point where water lines and drains may freeze.

To investigate the adequacy of code requirements at providing combustion air under all types of weather conditions, a field study was undertaken to measure the air infiltration rates in houses fitted with combustion air openings. Two configurations were tested—one with the openings exposed directly to the wind—the other sheltered from the wind.

The Uniform Mechanical Code[1] lumps together all the air requirements (combustion, draft hood dilution and space conditioning) and refers to the sum as the combustion air requirement. Chapter 30 of the *1996 ASHRAE Handbook—HVAC Systems and Equipment*[2] contains a set of guidelines for sizing and installation considerations for combustion air systems. In the latter reference, the air required for combustion and draft hood dilution and that required for conditioning the equipment room are treated separately.

Other codes used in the United States include ANSI Z223.1 (NFPA 54) (National Fuel Gas Code)[3] and the Gas Engineers Handbook.[4] In Canada, the equivalent codes are CAN/CGA-B149.1 (natural gas)[5] and CAN/CGA-B149.2 (propane).[6] All of these codes and guidelines may apply in both warm and cold climates. As such, some contain statements cautioning that heating the makeup air might be necessary.

Table 1 illustrates one method used to list the size requirements for combustion air systems. This is taken from the 1997 edition of the Uniform Mechanical Code and can be used for oil or gas-burning equipment. A designer is advised to check with local authorities as to which co[...] they accept in their jurisdiction. Signi[...]cant differences exist between codes r[...]garding recommended sizes for openin[...] for a given appliance(s) input rating.

For example, consider a 73 k[...] (250 000 Btu/h) natural gas warm-air fu[...]nace equipped with a draft hood that [...] located in a confined space with an ext[...]rior wall, and tight construction. A co[...]fined space is defined as a room or spa[...] having a volume of less than 4.8 m^3 p[...] kW (50 ft^3 per 1,000 Btu/h) of total inp[...] rating of all appliances in that space. F[...] this situation, the Uniform Mechanic[...] Code requires two openings each with [...] free area of 40 325 mm^2 (62.5 $in.^2$). The [...] is obtained directly from outdoors or fro[...] a space that is freely communicating wi[...] outdoors.

The Canadian Code (natural gas only[...] however, requires only one direct ope[...]ing to the outdoors with a free area of [...] 000 mm^2 (36 $in.^2$) for the same configur[...]tion. This is shown in *Table 2*, which [...] for use with appliances equipped wi[...] draft hoods or draft regulators, such [...] barometric dampers, and tight constru[...]tion. The Uniform Mechanical Code r[...]

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cently has been changed to permit a single opening when the appliance is in a confined space with tight construction and the air is obtained from outdoors or a space freely communicating with the outdoors. For the example furnace, the opening required would be 54 000 mm^2 (83 in.^{2}).

If the construction is not tight, for the same furnace in a confined space, the Canadian Code and the Uniform Mechanical Code requirements remain the same as before. For the case where the construction is not tight and the furnace is unconfined, the Uniform Mechanical Code requires no specific openings, while the Canadian Code requirement remains as before—a single opening of free area 23 000 mm^2 (36 in.^{2}).

Most codes and handbooks require that the air supply be through two permanent openings: one placed low in a wall of the room and the other near the ceiling. Two openings are specified, it is surmised, because of the possibility of the flue(s) being blocked. If this happens, flue gas spillage will occur. With two openings, these gases can exit through the upper opening while adequate air volumes are still being supplied for combustion through the lower opening. This avoids significant carbon monoxide and/or unburned fuel buildup in the space. The openings must always communicate directly with the outdoors or an unconfined space and should not be ducted together so that if the flue becomes blocked, the fail-safe venting of flue gases can occur.

The size of the openings is selected according to the guidelines listed in *Tables 1* and 2. This should ensure sufficient air for combustion and space conditioning when the appliances are fired, regardless of the time of year. Proper sizing of openings or supply systems is essential in cold regions because the normally tighter construction techniques prevent significant air infiltration through the building envelope to the appliance space.

The single opening permitted in *Table 1* must be located within the upper 305 mm (12 in.) of the enclosure. This provision in the Uniform Mechanical Code is based on a recent study by the Gas Research Institute.[7] The Canadian Code requires single openings to be fitted with a duct that normally terminates within 300 mm (1 ft) above and within 600 mm (2 ft) horizontally from the burner level of the appliance having the largest input energy. Exceptions can be granted by the authority having jurisdiction. Field testing of a one-opening system was not done in this experimental program.

In regions with cold climates, permanent openings for air supply can create operational problems. The large indoor-outdoor temperature difference can produce excessive flow through the openings. Not only is the volume flow rate of air increased with increased temperature difference, low outdoor temperatures increase the density of the incoming air, further increasing the mass flow rate.

For example, lowering the ambient temperature from 10°C (50°F) to –40°C (–40°F) increases the density of the air by about 18%. As these flows are continuous, cooling the interior of equipment rooms to the point where water pipes, floor drains and equipment can freeze is a distinct possibility. Problems of this nature normally are not discovered until after startup of the equipment, resulting in remedial action being required—usually a costly ven-

Buildings of Ordinary Tightness		Buildings of Unusually Tight Construction[2]	
Condition	Size of Opening or Ducts × 0.293 for W × 645.2 for mm^2	Condition	Size of Openings or Ducts × 0.293 for W × 645.2 for mm^2
Appliance in unconfined[2] space:	May rely on infiltration alone	Appliance in unconfined[2] space: Obtain combustion air from outdoors or from space freely communicating with outdoors.	Provide two openings, each having 1 in.^{2} per 5,000 Btu/h input. Ducts admitting outdoor air may be connected to the cold-air return.
Appliance in confined[3] space: 1. All air from inside building.	Provide two openings into enclosure each having 1 in.^{2} per 1,000 Btu/h input freely communicating with other unconfined interior spaces. Minimum 100 in.^{2} each opening.[4]	Appliance in confined[3] space: Obtain combustion air from outdoors or from space freely communicating with outdoors.	1. Provide two vertical ducts or plenums, 1 in.^{2} per 4,000 Btu/h input each duct or plenum. 2. Provide two horizontal ducts or plenums; 1 in.^{2} per 2,000 Btu/h input each duct or plenum.
2. Part of air from inside buiding.	Provide two openings into enclosure[4] from other freely communicating unconfined[2] interior spaces each having an area of 100 in.^{2}, plus one duct or plenum opening to outdoors having an area of 1 in.^{2} per 5,000 Btu/h input rating. The outdoor duct or plenum opening may be connected to the cold-air return.		3. Provide two openings in an exterior wall of the enclosure; each opening 1 in.^{2} per 4,000 Btu/h input. 4. Provide one ceiling opening to ventilated attic and one vertical duct to attic; each opening 1 in.^{2} per 4,000 Btu/h input. 5. Provide one opening or one vertical duct or one horizontal duct in the enclosure; 1 in.^{2} per 3,000 Btu/h input but no smaller than vent flow area.
3. All air from outdoors. Obtain from outdoors or from space freely communicating with outdoors.	Use any of the methods listed for confined space in unusually tight construction as indicated in the right column, "Buildings of Unusually Tight Construction."		6. Provide one opening in enclosure ceiling to ventilated attic and one opening in enclosure floor to ventilated crawl space; each opening 1 in.^{2} per 4,000 Btu/h input.

[1] For location of openings, see Section 702. [2] As defined in Section 223. [3] As defined in Section 205. [4] When the total input rating of appliances in enclosure exceeds 100,000 Btu/h (29.3 kW), the area of each opening into the enclosure must be increased 1 in.^{2} (645 mm^2) for each 1,000 Btu/h (293 W) over 100,000 (29.3 kW).

***Table 1**: Size of combustion air openings or ducts (source: Uniform Mechanical Code 1997, Table 7-A).*

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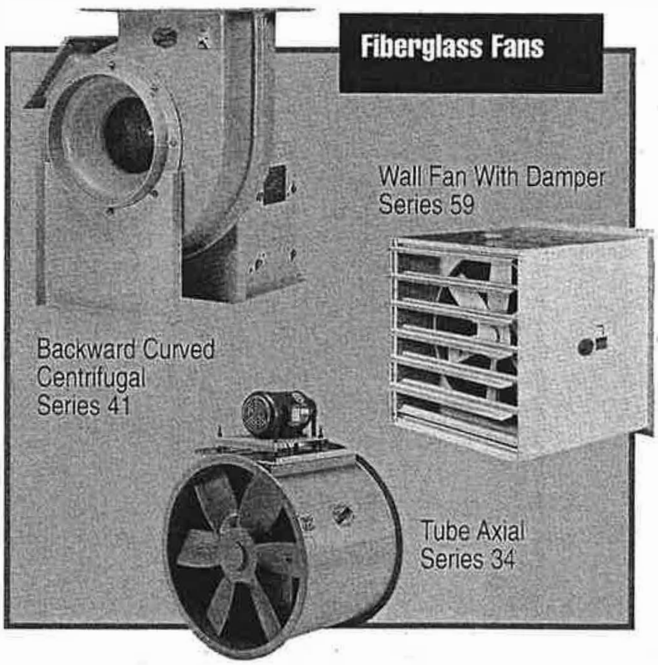

ture. An additional concern is that the codes show no technical basis for the sizing required and provide little information that would allow a designer flexibility in an installation. This means that the latitude afforded by the codes for "professionally designed" installations rarely is invoked.

Description of Field Monitoring

With this as background, a study was undertaken to determine if the present code requirements for combustion air supply openings are proper or require modification, and whether an alternate method could be designed and tested that would overcome some of the reported operational problems. The experimental part of the study was done principally in two houses. A third house was used to test a prototype design.

The electrically heated houses are representative of current tight construction methods and are located in a northern climate. Two of the houses have 152 mm (6 in.) diameter Type B vents fitted with 76 mm (3 in.) diameter orifices for metering, while the third has no vent.

The pairs of combustion air openings (*Figure 1*) were fitted in exterior walls of the houses, communicating directly with the outdoors. One pair was placed in a completely exposed position, the other, in the second house, in a wall facing an adjacent house approximately 2.6 m (8.5 ft) away. The locations are shown in the legend boxes in *Figures 2* and *3* respectively. These boxes are plan views of the test site giving the compass direction, flue location and combustion air openings location designated as C/A VENT. The second pair of openings, located between two houses, were sheltered from most winds at the test site. In both cases, the openings were mounted within 300 mm (12 in.) of the floor and ceiling elevations as required by the Uniform Mechanical Code.

The openings selected for the study were rectangular, 356 × 254 mm (14 × 10 in.) nominal size, with a 6 mm (0.25 in.) mesh screen and motorized low leakage dampers. A pair of openings of this size, according to the Uniform Mechanical Code, would be sufficient for a 73 kW (250 000 Btu/h) appliance. The sizing was based on 30% excess air for combustion, an extra 30% for draft hood dilution and assuming a 50% net free area due to the mesh screen and open dampers. The openings should flow about 120 m^3/h (70 cfm) under all conditions. If this size of furnace had been installed in the test houses, it would be considered as being in a confined space. More than 2,700 hours of field testing was done with these original openings. The gross flow area of the openings was later reduced to 356 × 127 mm (14 × 5 in.), i.e., half the size. These were field tested for more than 5,600 hours.

The plan area of the test houses is about that of a large two-car garage (49 m^2 [528 ft^2]). They were constructed with full-height walls and basements. As there are no interior partitions, the above and below grade portions of each house consists of a single room. The volume of each room is about 113 m^3 (4,000 ft^3). The houses were originally constructed to have low levels of air infiltration, i.e., tight construction. Installing combustion air intakes of the size used in this study meant that these openings would be the dominant leakage sites for air infiltration.

The air infiltration rates were measured using a Sulphur Hexafluoride (SF_6) continuous tracer gas technique.[8] The system consists of a computer-controlled sampling and SF_6 injection system, and an infrared detection instrument tuned to 10.6 μm, a strong absorption band for SF_6. The SF_6 level in each house was measured, and metered volumes of SF_6 were injected to maintain a level of 5 ppm of the tracer gas. Knowing the active volume of each house and the amount of SF_6 required to maintain 5 ppm for each time period, permits direct evaluation of the air infiltration rate for that period.

One and a half years of hourly air infiltration data was gathered in the study. During the study, the outdoor temperature varied from +31°C to –41°C (88°F to –42°F), while hourly average wind velocities varied from 0 to 12 m/s (0 to 27 mph).

Total Input of Appliances* Thousands of Btu/h (kW)	Required Free Area of Air Supply Opening or Duct Square Inches (mm²)	Acceptable Approximate Round Duct Equivalent** Diameter in Inches (mm)
25 (8)	7 (4500)	3 (75)
50 (15)	7 (4500)	3 (75)
75 (23)	11 (7000)	4 (100)
100 (30)	14 (9000)	4 (100)
125 (37)	18 (12 000)	5 (125)
150 (45)	22 (14 000)	5 (125)
175 (53)	25 (16 000)	6 (150)
200 (60)	29 (19 000)	6 (150)
225 (68)	32 (21 000)	6 (150)
250 (75)	36 (23 000)	7 (175)
275 (83)	40 (26 000)	7 (175)
300 (90)	43 (28 000)	7 (175)
325 (98)	47 (30 000)	8 (200)
350 (105)	50 (32 000)	8 (200)
375 (113)	54 (35 000)	8 (200)
400 (120)	58 (37 000)	9 (225)

* For total inputs falling between listed figures, use next largest listed input. ** These figures are based on a maximum equivalent duct length of 20 ft (6 m). For equivalent duct lengths in excess of 20 ft (6 m) up to and including a maximum of 50 ft (15 m), increase round duct diameter by one size.

Table 2: Size of combustion/dilution air openings or ducts for appliances having draft control devices when the combined input is up to and including 400,000 Btu/h (120 kW) and the structure is of tight construction (source: Natural Gas Installation Code, CAN/CGA-B149.1-M91).

Field Test Results

The field testing was done with the dampers either fully open or fully closed for 24 hours in an alternating pattern. No attempt was made to modulate the dampers to control flow. A typical set of results is shown in *Figure 2* for the unsheltered large area openings during a March to September period. The structure does not have an open vent, thus the change in air infiltration rates are representative of what would occur during periods when the appliances were not fired. With the dampers closed, the average air infiltration rate was 17.7 m^3/h (10.5 cfm), *Figure 2a*. With the dampers open, the average increased to 131 m^3/h (77 cfm), *Figure 2b*, slightly above the design value of 120 m^3/h (70 cfm). Note the large variation in the air infiltration rates with the dampers open, *Figure 2b*, compared with those when the dampers were closed. This shows the dominance of the open dampers as leakage sites for air infiltration in this tightly built structure. Measured values ranged from about 20 m^3/h (11.8 cfm) to more than 300 m^3/h (177 cfm)—a 15-to-1 variation in volume flow rate. The sheltered openings, which were installed in a house with an open vent, showed similar average air infiltration rates but less variation. The variation was about 10-to-1 as compared to 15-to-1 for the case of unsheltered openings. Prior to the installation of the dampers, the open vent was the dominant leakage site in this house. Air infiltration in structures results from wind pressure and buoyancy effects. Thus, installing the combustion air openings in a sheltered location should show reduced variation with wind speed, but not necessarily total flow rate if significant buoyancy effects are present.

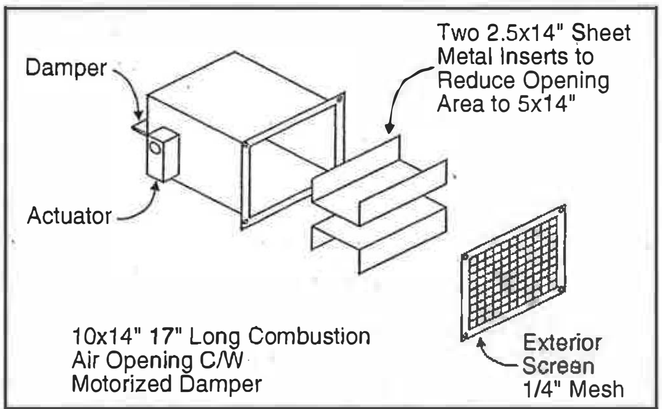

Figure 1: Detail of combustion air opening and area reduction method.

A wind rosette for the spring and summer conditions at the site also is shown in *Figure 2*. The lengths of the lines give the frequency of the wind for that direction. The outer circle represents 10% of the time, while the number in the center is the percentage of the time that calm conditions exist. The dominant wind directions for the site are from the SE and S (135 to 180

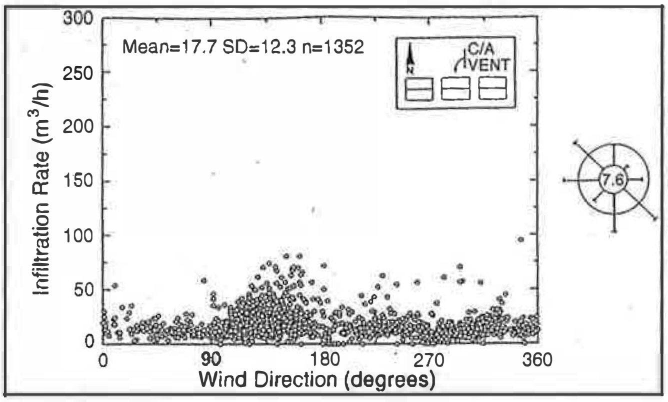

Figure 2a: ***Measured ventilation rates in House 3 with unsheltered combustion air vents closed, 1,352 hours.***

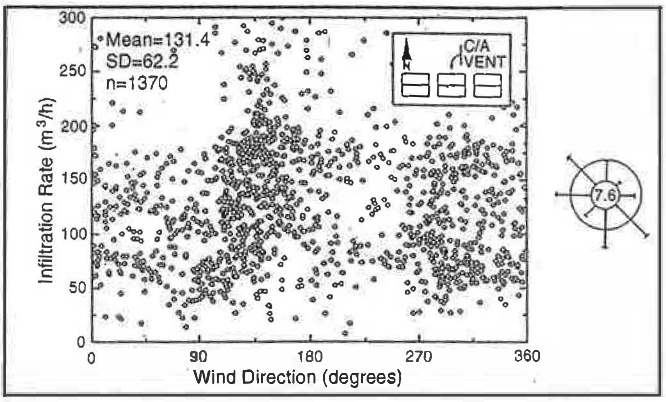

Figure 2b: ***Measured ventilation rates in House 3 with unsheltered combustion air vents open (two vents, each 356 × 254 mm [14 × 10 in.]), 1,370 hours (spring and summer conditions).***

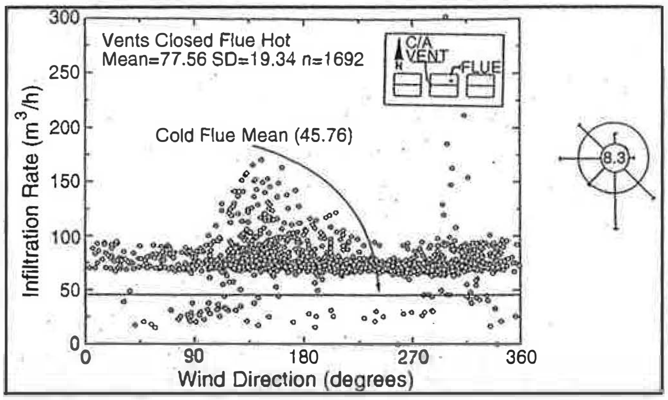

Figure 3a: ***Measured ventilation rates in House 4 with sheltered combustion air vents closed, heated flue, 1,692 hours.***

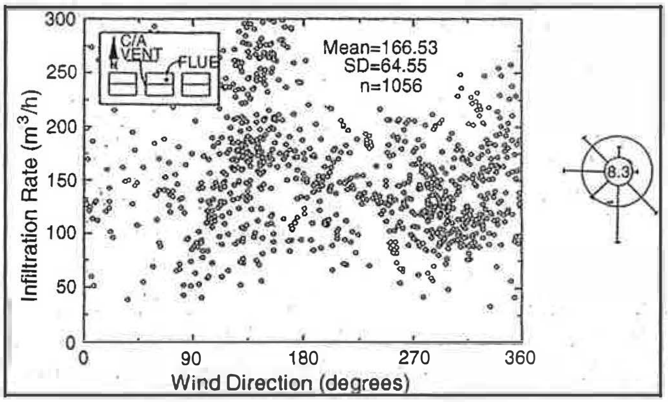

Figure 3b: ***Measured ventilation rates in House 4 with sheltered combustion air vents open (two vents, each 356 × 127 mm [14 × 5 in.]), heated flue, 1,056 hours (winter conditions).***

degrees), and the W and NW (270 to 315 degrees), accounting for the large number of data points shown in these regions. Wind rosettes for meteorological sites in the United States and Canada are found in standard references such as The Weather Almanac,[9] Climatic Atlas of the United States[10] and Climatological Atlas of Canada.[11]

When the flow area of the openings was cut in half, a corresponding reduction in flow was not obtained—rather the measured flow rates remained almost the same! To fit the openings with effective motorized dampers, a short length (30 cm [12 in.]), of rectangular duct had to be added for the dampers to seal against. Thus, when the face area was reduced in half using the U-shaped pieces shown in *Figure 1*, the openings were no longer geometrically similar and they exhibited different flow characteristics. In particular, the coefficient of discharge increased, offsetting the reduced flow area, allowing the same volume flow rate to pass for a given pressure differential. This effect was verified through laboratory determination of the head-flow characteristics of full-sized and reduced area openings. When detailing these openings, the designer should check the coefficient of discharge of the configuration(s) specified to ensure proper flow characteristics.

Heating the Vent

Heating the vent adds buoyancy and increases the air infiltration rate of a structure. To study this influence, the open vent in the house with the sheltered combustion air openings was heated electrically to simulate appliance firing. The heater added 3 kW (10 200 Btu/h) to the vent gases, simulating a 15 kW (50 000 Btu/h) input rating appliance at 80% efficiency. The vent was heated in a 24-hour on, 24-hour off pattern, 12 hours out of phase with the damper cycle. Thus, it was possible to collect air infiltration data for all four configurations; closed dampers/cold vent, closed dampers/hot vent, open dampers/cold vent and open dampers/hot vent.

Figure 3a clearly illustrates the influence of the hot vent when the combustion air openings are closed, but its influence is not so obvious with open combustion air openings, *Figure 3b*. With the combustion air openings closed and the vent unheated, the mean air infiltration rate was 45.8 m³/h (27 cfm) as identified on *Figure 3a*. When the vent was heated, the mean rose to 77.6 m³/h (46 cfm), an increase of 31.8 m³/h (19 cfm).

For the case of the open combustion air openings, *Figure 3b*, the mean air infiltration rate rose only by 20.2 m³/h (12 cfm) from 146.3 m³/h (86 cfm) to 166.5 m³/h (98 cfm). This illustrates that the influence of a particular driving force on air infiltration rate is dependent on the leakage characteristics of the structure. The large variability in infiltration rates persists, *Figure 3b*, even though the open vent adds 50% to the leakage area of the house when the combustion air openings are closed. This

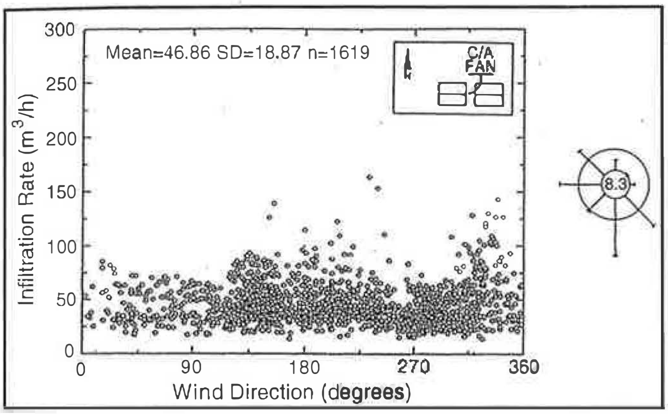

Figure 4a: Measured ventilation rate in House 1, mechanical combustion air supply fan off, unheated flue, 1,619 hours.

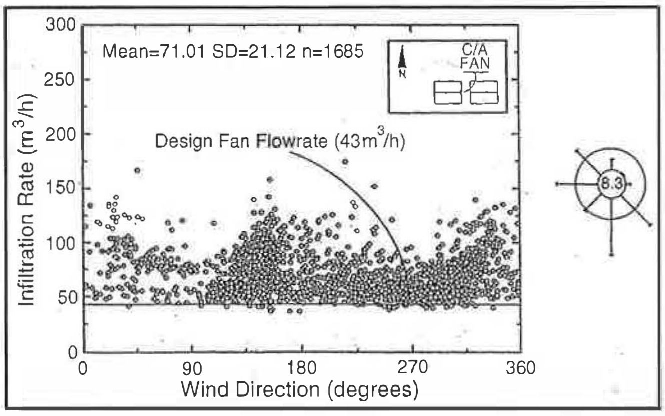

Figure 4b: Measured ventilation rate in House 1, mechanical combustion air supply fan on, unheated flue, 1,685 hours (winter conditions).

is a direct result of the variability in ambient conditions over the length of the test period. The wind rosette shows again that the dominant wind directions are from the SE and S (135 and 180 degrees) and the W and NW (270 and 315 degrees).

Mechanical Supply

Because the passive openings showed a large variation in air infiltration rate under the influence of wind and temperature, and because the minimum design flow rate could not be guaranteed with the open combustion air openings under all conditions, a mechanical combustion air supply system with a flow control orifice was tested in the third house. The air was supplied by a small centrifugal fan that was run on a 24-hour on, 24-hour off cycle. For the design flow rate of 43 m^3/h (25 cfm), it produced a pressure drop of 125 Pa (0.5 in. H_2O) across the flow control orifice. This design was selected so that the interior pressure would be kept near ambient by removing, with the orifice plate, the pressure rise generated by the fan. As such, the smaller indoor-outdoor pressure differentials generated by the wind and buoyancy had little effect on the flow through the system.

Figure 4 shows the results of the field testing. It is clear that the fan system provides an assured airflow near the design value and that the variability about the mean is reduced, especially when compared to the results in *Figures 2* and *3*. The use of such a system would have to be approved by local authorities as a "professionally designed" system. Appropriate safeguards and interlocks would be needed. These are readily available. Additional testing of this concept in other types of structures is necessary. Safety standards and testing procedures for such units also are required. At present, codes such as ANSI Z21.47-1993,[12] do not address this issue. These would be necessary to make this method generally acceptable to code authorities. However, most codes permit power-activated equipment to be placed in the combustion air supply system provided it is electrically interlocked with the main burner fuel-supply valve so as to prevent fuel delivery if the system fails to function properly. Such systems are commercially available.

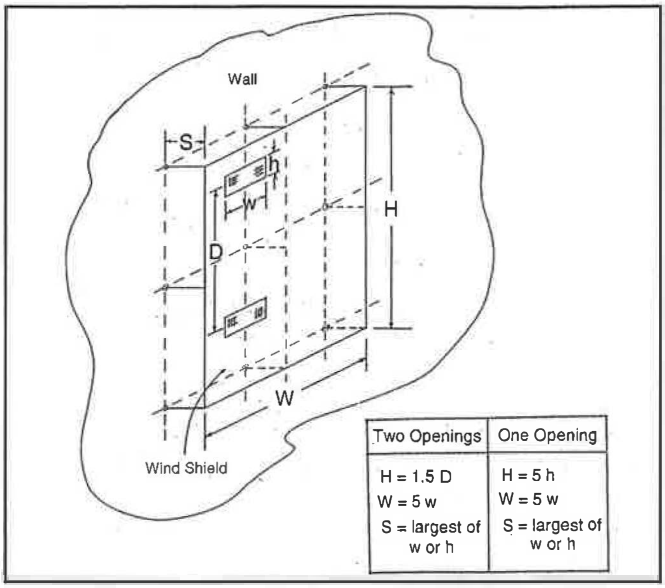

Figure 5: Recommended dimensions for wind shields placed symmetrically over combustion air openings.

Designers Checklist

To assist the designer of combustion air systems the following checklist, based on the conclusions of the experimental study, is presented. It should be used when designing either combustion air openings or a mechanical air supply system. Recall that mechanical supply of combustion air is not considered in present codes and only can be treated as an engineered system requiring approval. In either case, the designer should check with local authorities as to which code(s) they have adopted for their jurisdiction.

1. Passive Combustion Air Openings

a. The design and installation must meet all the code requirements for the jurisdiction. Thus, over-ventilation may occur in winter months and the consequences should be considered in the design.

b. Most locations have variable wind velocity and direction. Flow through unsheltered passive combustion air openings due to these variations is not easily predicted, thus there is no preferred location for unsheltered combustion air openings.

c. In locations where there is a dominant wind direction and possible channelling effects due to surrounding structures, especially consider the location of the combustion air openings so that the natural circulation effects of buoyancy due to their vertical separation are not dominated by wind effects.

d. Placing combustion air openings in a sheltered location, i.e., between buildings or separate towers on a building, will reduce the flow variability. The *1997 ASHRAE Handbook—Fundamentals*,[13] Chapters 15 and 25, presents data on shielding effects of other buildings and Local Shielding Classes. If shielding by nearby structures is deemed insufficient, consider constructing a shield. *Figure 5* can be used as a guide.

e. Locate openings so that the discharge into the equipment room is remote from water pipes, floor drains and pumps that contain fluids susceptible to freezing.

f. Use dampers with interlocks to fuel supply valves to control air infiltration when combustion air is not required. Install dampers near the penetration of the building envelope.

g. Continuous mixing of the room air during damper open periods can help prevent pooling of cold air and reduce the possibility of freezing equipment.

h. Use sensors to detect flue gas spillage. A warning signal should be given, as well as interlocking the sensors to the fuel supply valves.

i. Specify adequate air/vapour retarder for the envelope of the appliance space.

j. Insulate all ducts connected to the exterior to prevent moisture condensation.

k. Use fin-coil heaters to temper the combustion air. However, they cannot be installed in the ducts communicating directly to the exterior due to the possibility of blockage. Only the non-freeze type of fin-coil heaters should be used. See Chapter 31, *1996 ASHRAE Handbook—HVAC Systems and Equipment*.[2]

l. Consider separating the space conditioning air from the combustion air. This would allow control of room conditions independent of the firing of appliances.

m. If the mechanical room is pressurized, the door should be kept closed and fitted with weather stripping to prevent migration of combustion products to other parts of the building. If not pressurized, weather stripping is not necessary.

n. Consider placing carbon monoxide detectors in the mechanical room and the adjoining rooms.

o. In climates with significant snowfall and a propensity for hoar-frost formation a screen mesh larger than 6 mm (0.25 in.) should be used.

2. Mechanical Supply

a. Use a fan with an outlet flow control device such as an orifice plate. The fan-generated pressure should be the dominant driving force for the air supply rather than natural driving forces. Thus, it is recommended that the pressure drop across the flow control exceed the wind pressure acting on the structure if the wind velocity were three times the average wind velocity at the site. This will ensure an adequate supply of combustion air under all environmental conditions. A hot flue will add to the pressure differential but have little effect on the air infiltration rate.

For example, the test site's mean wind speed is 3.6 m/s (8.1 mph). Tripling this velocity would generate a pressure of about 72 Pa (0.29 in. H_2O). Thus, the orifice should be sized to have a pressure drop of this value at the flow rate desired for providing the proper amounts of combustion air. Since the wind speed is only above three times the mean velocity for short periods of time, the flow through the air delivery system will remain almost constant. Heating the flue to 200°C, in a 0°C ambient, produces a buoyancy pressure of 25 Pa (0.1 in. H_2O) if the flue is 5 m (16 ft) tall. This will add only 15 % to the airflow through the system.

b. A parallel path supply system must be provided so that air delivery is assured in the case of failure of equipment in the air supply system. This should be a dampered passive system safety interlocked to the fuel supply valves or a second fan system.

c. When the equipment room contains more than one combustion device, e.g., several boilers or heaters for staging, consider having an equal number of mechanical supply systems, each sized to match the requirements of a particular combustion device and safety interlocked thereto.

d. Statements h through o apply.

Acknowledgments

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