ENDIX 3

ORATORY EVALUATION OF RANGE HOOD AND BATHROOM ᴇxʜAUST COMPONENTS AND SYSTEMS

Final Report No. ES/ESC-88-25

LABORATORY EVALUATION OF RANGEHOOD AND BATHROOM EXHAUST COMPONENTS AND SYSTEMS

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1.0 INTRODUCTION

In 1976 the Canadian Standards Association published the "Installation Code for Residential Mechanical Exhaust Systems" (C.S.A. C260.1-1975) [1]. The standard was intended to improve home ventilation by improving exhaust system installation practice. With increasing concern about Indoor air quality and today's "tighter" construction practice, the need to have properly installed residential air exhaust equipment is now seen as more important than twelve years earlier when the code was published.

Proper design of exhaust systems depends on the availability of accurate information on exhaust fan flow and the system component pressure drop characteristics. Pressure drop characteristics through most exhaust system components have been well investigated. However, there is little information on the pressure drop through wall caps and roof caps. Furthermore, according to unpublished manufacturer's data, the pressure drop across wall and roof caps was found to be a significant portion of the total system pressure drop. Consequently the design of residential exhaust systems is hampered by a lack of reliable performance data on critical components in the system. Therefore, there is a need to measure pressure drops through these components for a range of flows, to check on existing manufacturer's data, and to enable the industry to design effective exhaust systems.

Field observations have indicated that most exhaust systems are not properly designed or properly installed despite the installation standard. Due to improper design, the volume flow rate is reduced in most of these installations. However, it was not known whether or not this reduction was significant or which installation flaws were of greater consequence. A series of laboratory tests were needed to assess the impact of installation or design errors on exhaust system airflow.

2.0 OBJECTIVE AND SCOPE

The main objective of this laboratory program was to fill the gap in existing knowledge of pressure loss characteristics of residential exhaust components and systems. The scope of this work included tests:

- to confirm a manufacturer's pressure drop claims for several wall caps and roof caps;

- to determine, through sequential introduction of substandard components, the performance degradation from ideal to worst-case for both bathroom and kitchen exhaust systems.

A supplementary objective of this program was to compare duct loss measurements done by ORF to those done by ASHRAE, and to the accepted loss characteristics for turbulent pipe flow. This was done as a check on ASHRAE's measurements, and as a check on the experimental techniques used in this program.

3.0 RATIONALE FOR THE LABORATORY LAYOUT OF THE BATHROOM AND RANGE HOOD EXHAUST SYSTEMS

The method used in finding the volume flow rate through range hood and bathroom exhaust systems involves setting up a representative system in a laboratory, and taking measurements. Information on representative installations of exhaust systems was obtained from field investigations directed by Mr. R. Bach of H.R.A.I./T.S.D.I. The objective of the field investigations was to observe installation procedures, to identify the range of makes and models of fans installed, and to undertake airflow and noise measurements. These investigations involved visits to building sites in Oakville, Mississauga, Halifax, Quebec City, Calgary, and Vancouver.

The systems tested in the laboratory were based on these field observations and are described in detail in Sections 4.3 and 4.4 .

The range hoods and bathroom fans used in the laboratory testing were mid-priced units. These units were observed to be occasionally installed and performed better than the low cost 'builder' models.

4.0 TEST PROCEDURE

The volume flow rate measurements done in this program made use of the ORF nozzle chamber. Details on this equipment are contained in Appendix I. This device was checked against a Laminar Flow Element. It was found that volume flow measurements obtained from these two instruments differed by less than 1.5 %.

4.1 Pressure Drop Characteristics of Commercial Wall Caps

Three wall caps were tested. These wall caps are described below:

<u>Bathroom Exhaust System Wall Cap</u>
This wall cap is manufactured by a major manufacturer of bathroom and range hood exhaust equipment. It will join to a 100 mm (4 inch) duct directly, or to a 75 mm (3 inch) duct through a transition. It has a single spring loaded damper.

<u>Range Hood Exhaust System Wall Cap</u>
Like the bathroom exhaust wall cap, this wall cap is manufactured by a major manufacturer of bathroom and range hood exhaust equipment. It joins to 85 x 255 mm (3.25 x 10 inch) rectangular duct. It has a spring loaded damper.

<u>Deflecto Dryer Vent - 4 Inch Single Damper</u>
The Deflecto dryer vent is similar to the bathroom exhaust wall cap. Like the bathroom unit, it fits to 100 mm (4 inch) duct and has a single damper. However, its damper is gravity operated only.

The wall caps were connected to the ORF nozzle chamber as shown in Figure 1. The upstream section of duct was 100 mm (4 inch) diameter duct for the bathroom

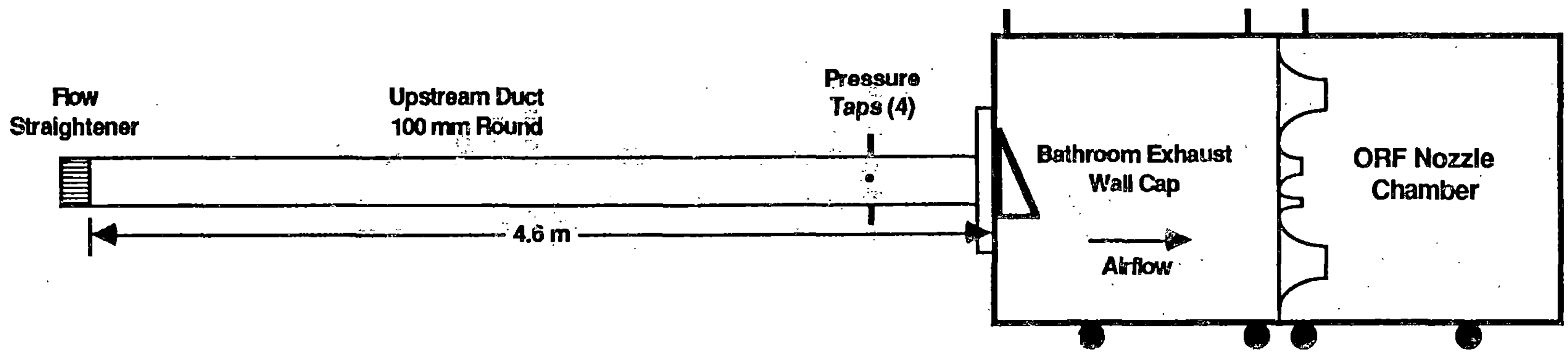


Figure 1: Typical Set-up for Bathroom Wall Cap

exhaust wall cap, and 85 x 255 mm (3.25 x 10 inch) duct for the range hood exhaust wall cap. The length of duct was about 4.6 m. The wall cap was therefore 46 diameters downstream of the duct inlet for the 100 mm duct, and 28 hydraulic diameters downstream of the duct inlet for the 85 x 255 mm duct. This was sufficient to ensure fully developed flow. All joints and seams were sealed with tape.

The pressure drop across the wall caps and the dryer vent cap was measured for flow rates ranging from about 7 L/s to about 170 L/s for the bathroom exhaust wall cap, from about 7 L/s to about 200 L/s for the range hood exhaust wall, and from about 9 L/s to about 180 L/s for the Deflecto dryer vent cap.

Determination of Wall Cap Pressure Drop at Standard Temperatures and Pressures

In order to allow comparison to other experimental data, it was necessary to convert both the pressure drop measurements and the corresponding volume flow rates to values that would occur at standard air conditions. This conversion can be done through an approach used by ASHRAE. According to ASHRAE [2], the pressure drop through entries, exits, elbows, diffusers, transitions, and obstructions can be expressed as:

$$\Delta P_t = C_o P_{v,o}$$

where:

- ΔP_t is the pressure drop through the device in question (Pa)
- C_o is the pressure drop coefficient for the device (dimensionless)
- $P_{v,o}$ is the dynamic pressure at the device (Pa)

The dynamic pressure is given by:

$$P_{v,o} = 0.5 \rho U^2$$

where:

- ρ is the density of air at the device's entrance (kg/m^3)
- U is the mean air velocity at the device's entrance (m/s)

It should be stressed that the above equations are applicable in all systems of units provided that only consistent units are used (eg: force in pounds, length in feet, time in seconds, mass in slugs).

Using the above formulae, the pressure drop that would occur at standard conditions is given by:

$$\Delta P_{t,s} = \Delta P_{t,a} \left(C_{o,s}/C_{o,a} \right) \left(\rho_s/\rho_a \right) \left(U_s/U_a \right)^2$$

where:

- $\Delta P_{t,s}$ and $\Delta P_{t,a}$ are the pressure drops at standard conditions and measurement conditions
- $C_{o,s}$ and $C_{o,a}$ are the pressure drop coefficients at standard conditions and measurement conditions

ρ_s and ρ_a	are the air densities at standard conditions and measurement conditions
U_s and U_a	are the air velocities at standard conditions and measurement conditions

The only unknown in the above equations is C_o. In examples cited in ASHRAE (such as several elbows), C_o is a function only of the geometry and the Reynolds number. Consequently, if the Reynolds number is the same for both measured and standard air conditions, the above equation can be simplified to:

$$\Delta P_{t,s} = \Delta P_{t,a} \, (\rho_s/\rho_a) \, (U_s/U_a)^2$$

The Reynolds number is given by:

$$R_d = \rho \, U \, d / \mu$$

where:

- R_d is the Reynolds number based on the duct hydraulic diameter
- d is the duct hydraulic diameter (m)
- μ is the viscosity at the wall cap's entrance (kg/m/s)

In order to ensure that that Reynolds number is the same for both measured and standard air conditions, the velocity at standard air conditions must be calculated using the formula (obtained by rearranging the Reynolds number formula) below:

$$U_s = (\mu_s / \mu_a) \, (\rho_a / \rho_s) \, U_a$$

where:

μ_s and μ_a	are the air viscosities at standard conditions and measurement conditions

4.2 Pressure Drop Characteristics of Commercial Roof Caps

Two roof caps were tested. These roof caps are described below:

<u>Bathroom Exhaust System Roof Cap</u>
This roof cap is manufactured by a major manufacturer of exhaust equipment. It can be connected to 100 or 75 mm (4 or 3 inch) diameter duct. Its damper is gravity loaded only.

<u>Range Hood Exhaust Eystem Roof Cap</u>
Like the bathroom exhaust roof cap, this range hood exhaust roof cap is manufacured by a major manufacturer of exhaust equipment. It connects to 85 x 255 mm (3.25 x 10 inch) rectangular duct. Its damper is both spring and gravity loaded.

The roof caps were connected to the Laminar Flow Element as shown in Figure 2. The

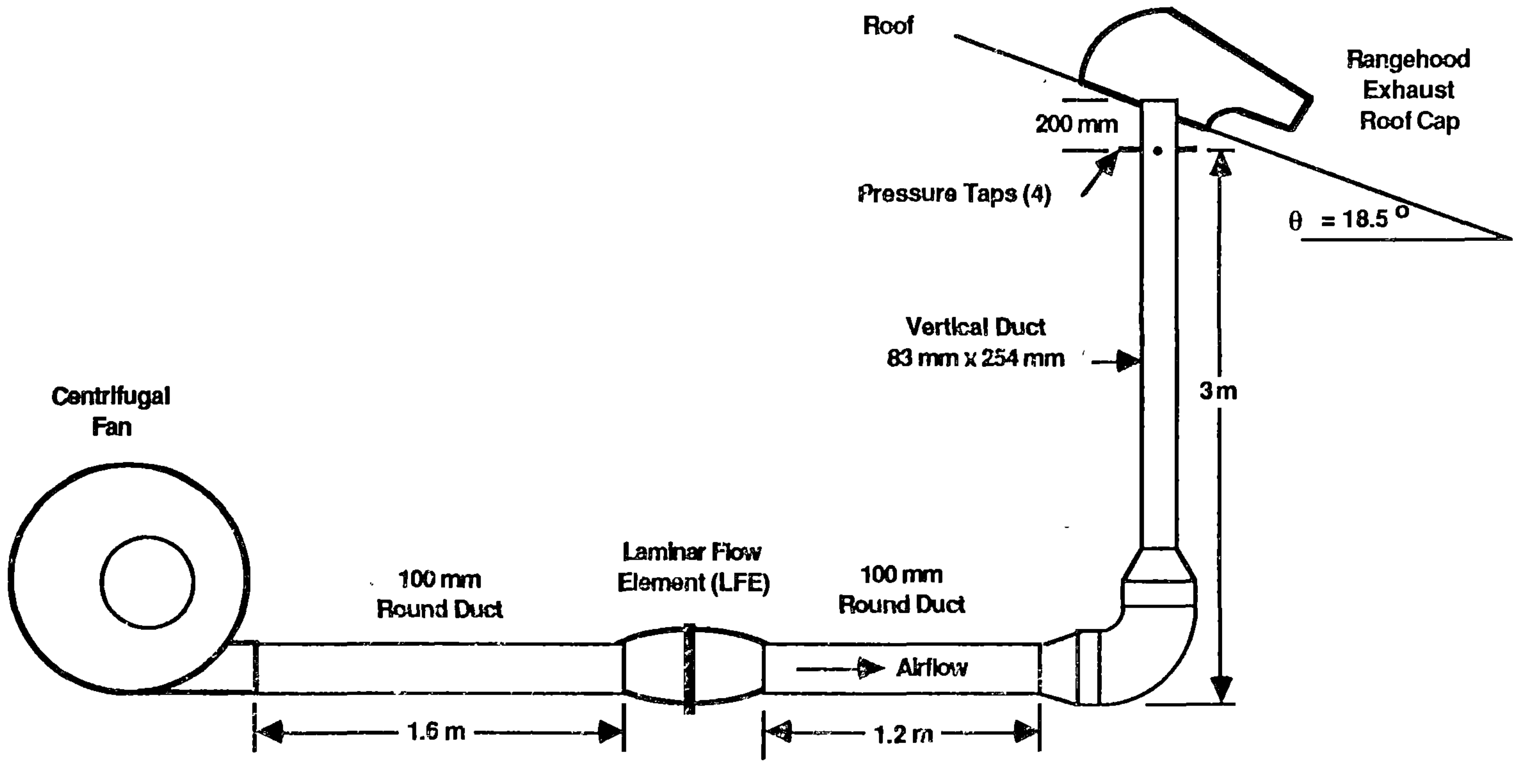


Figure 2: Test Set-up for Range Hood Roof Cap

upstream vertical section of duct was 100 mm (4 inch) diameter for the bathroom exhaust roof cap, and 85 x 255 mm (3.25 x 10 inch) for the range hood exhaust roof cap. The length of vertical duct was about 3 m. The roof cap was therefore about 30 to 45 diameters downstream of the elbow to ensure fully developed flow. All joints and seams were sealed with tape.

The pressure drop across the roof caps was measured for flow rates ranging from about 1.4 L/s to about 90 L/s for the bathroom exhaust roof cap , and from about 3 L/s to about 160 L/s for the range hood exhaust roof cap.

As with the wall cap test results, all measurements were converted to standard conditions, using the pressure coefficient/Reynolds Number technique described in Section 4.1 .

4.3 Volume Flow Rates Through Bathroom Exhaust Systems

The bathroom fan for this testing was a mid-priced unit. This fan has a centrifugal impeller, and is designed to use 100 mm duct. Its claimed volume flow at 2.5 mmWG static pressure is 38 L/s. Measurements of volume flow rate were obtained for the following installations:

- **Installation in Accordance with Manufacturer's Instructions**
  The layout of the system is shown in Figure 3. Installation was in accordance with the manufacturer's installation instructions. The wall cap was the previously tested bathroom exhaust wall cap. Ducting and elbows were 100 mm (4 inches) in diameter. The ducting was held together with sheet metal screws. The system was tested both with and without tape around the joints (the instructions do not mention taping the joints).

- **Typical Installation #1**
  The layout for this system is shown in Figure 4. The wall cap on this first typical installation was a 100 mm (4 inch) Deflecto dryer vent cap with multiple dampers. This was fitted with a 100 to 75 mm (4 to 3 inch) transition, and connected to 75 mm (3 inch) duct. All duct and elbows were 75 mm. The duct was connected to the bathroom fan through a transition. All ducting was held together with sheet metal screws. No tape was used.

- **Typical Installation #2**
  This installation was very similar to that described above. The only difference was that the wall cap was a 75 mm Deflecto dryer vent, and there was no transition at the wall cap.

- **Typical Installation #3**
  In this installation, 75 mm flexible duct was used throughout. The fan and wall cap are held in the same respective positions as in the previous installations. Two flexible pipe lengths were used: 5.5 and 7 m. These lengths are the actual lengths when the ducting is fully extended. The measured length of the duct, taking sags and bends into account was 5.1 and 5.7 m respectively. The duct

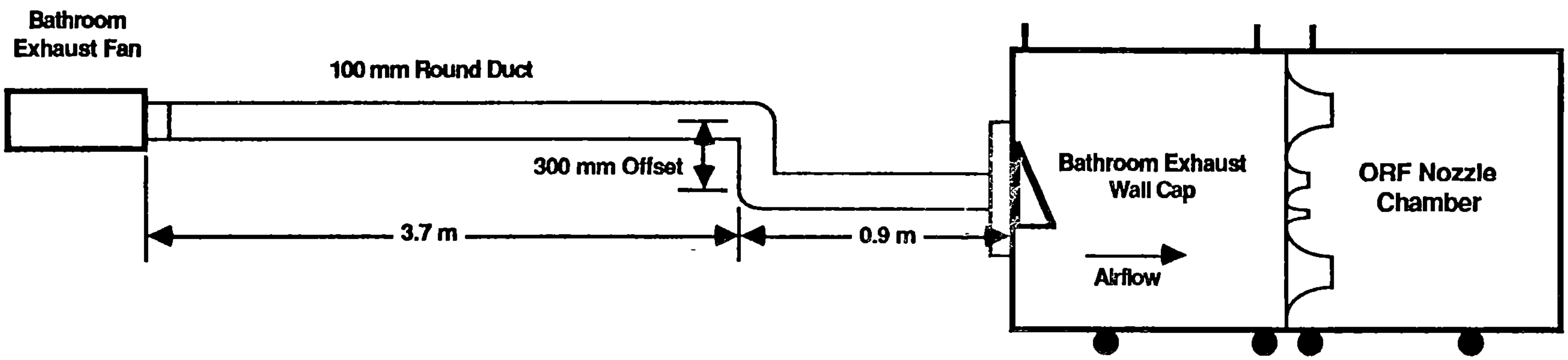


Figure 3: Washroom Exhaust Fan System Installation in Accordance with Manufacturer's Instructions

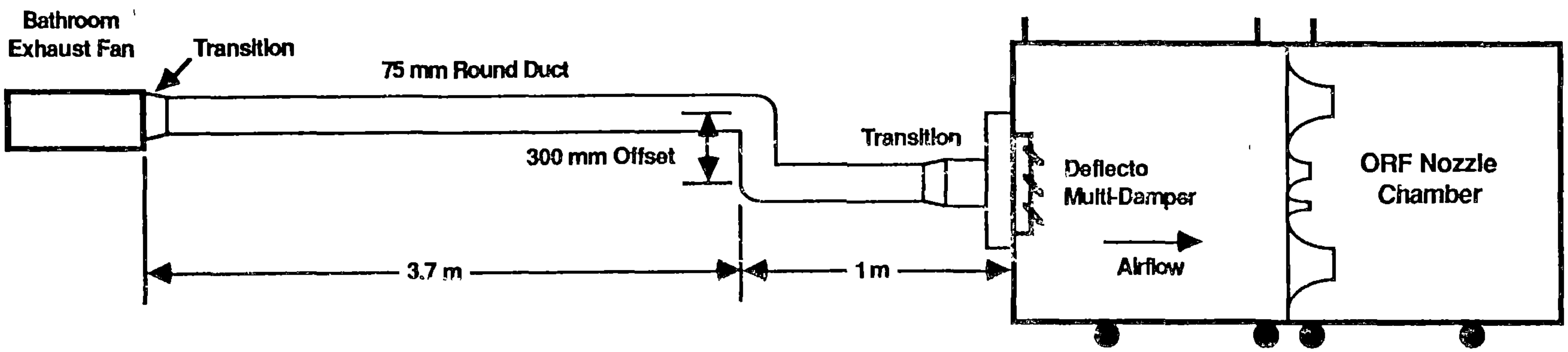


Figure 4: Washroom Exhaust Fan System - Typical Installation #1

joints were taped. The wall cap was the 75 mm Deflecto dryer vent.

The nozzle chamber was used to determine the volume flow rate exiting from the wall caps. This was done by first activating the bathroom fan. The nozzle chamber's blower was adjusted such that the static pressure at the wall caps' exit (in the nozzle chamber) was just below atmospheric pressure. The nozzle chamber blower was re-adjusted such that the pressure at the wall caps' exit was just above atmospheric pressure. The flow rate corresponding to atmospheric pressure was found by interpolating between the volume flow rates obtained in the previous two measurements. This volume flow rate was converted to standard air conditions.

This above described interpolation method was used for the following reasons:

- It was sometimes difficult to adjust the nozzle chamber blower such that the pressure at the wall cap's exit was atmospheric. The interpolation technique reduced the time required to conduct the experiments.
- Taking two pressure measurements at the wall cap's exit in the above described manner provided information on the sensitivity of the volume flow rate to the wall cap exit pressure. This indicated the significance of the uncertainty in the volume rate due to uncertainty in the wall cap exit pressure measurement.

In most of the above tests, the rotational speed of the bathroom fan was also measured. Using available data on the bathroom fan from [3], the pressure rise across the fan was determined. This was the pressure drop through the ducting corresponding to the volume flow rate at the wall caps' exit.

4.4 Volume Flow Rates Through Range Hood Exhaust Systems

The range hood used for this testing was a mid-priced unit. The unit has two centrifugal blowers driven by one electric motor. Ducting for the unit should be 85 x 255 mm. Its claimed volume flow at 2.5 mmWG static pressure is 94 L/s. The following systems were tested:

- **Installation in Accordance with Manufacturer's Instructions**
  The layout of the system is shown in Figure 5. Installation was in accordance with the range hood installation instructions. The wall cap was the previously tested range hood exhaust wall cap. Ducting and elbows were 85 x 255 mm (3.25 X 10 inch). The duct joints were taped.

- **Typical Installation**
  The layout of the system is shown in Figure 6. The wall cap was a Deflecto 100 mm dryer vent type. The ducting and elbows were 100 mm in diameter. The ducting was connected to the range hood through a 100 x 255 x 100 mm (4 x 10 x 4 inch) universal boot. Joints between the boot and the range hood were sealed with tape. The ducting was held together with sheet metal screws. No tape was used on the duct joints.

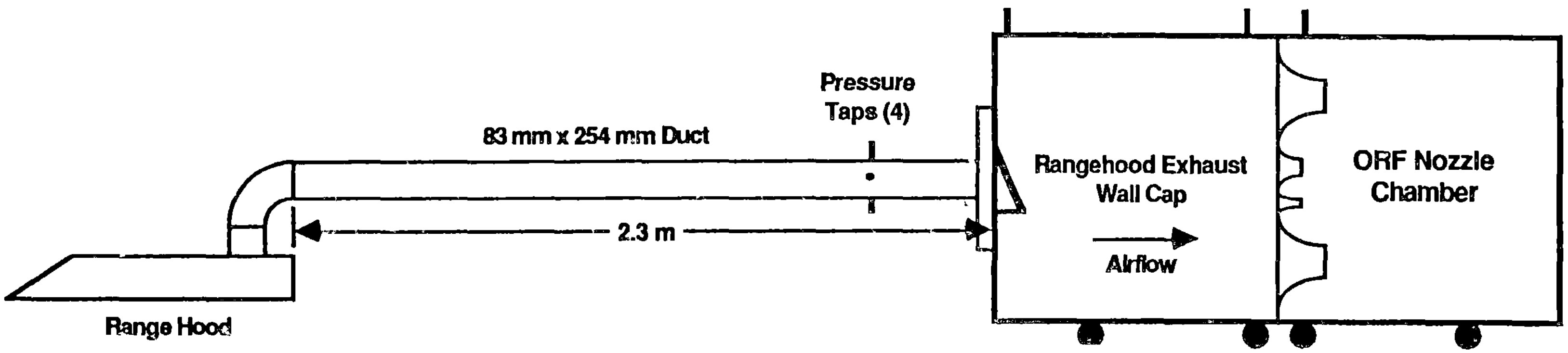


Figure 5: Range Hood with Wall Cap - Installation in Accordance with Manufacturer's Instructions

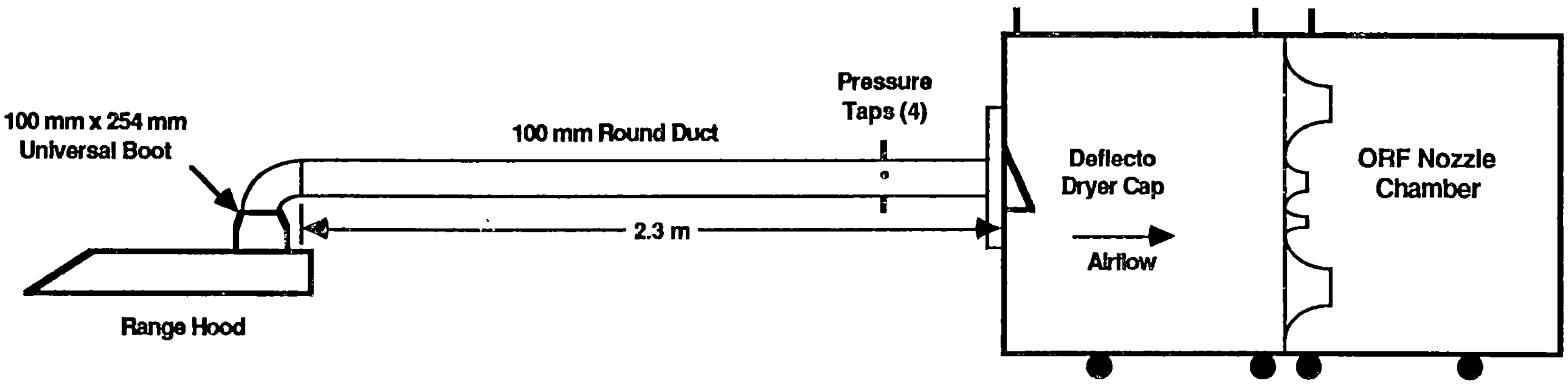


Figure 6: Range Hood - Typical Installation

The procedure followed for the testing of the range hood system was the same as that for the bathroom exhaust system.

4.5 Pressure Drop Through Ducting

A 100 mm round galvanized duct was used for this test. The test duct was made up of 3 short sections with approximate lengths of .7 m, .7 m and .5 m. Two short duct sections containing static pressure taps were connected to both ends of the test duct. All joints and seams were taped. The total length of the duct between the static pressure taps was 1.98 m. There were a total of 4 joints between the static pressure taps. This duct was then connected to the nozzle chamber as shown in Figure 7. To ensure fully developed flow, a 4.6 m section of duct was connected upstream of the upstream static pressure tap.

The static pressure drop between the taps was measured at several flow rates ranging between nominally 5 L/s and 140 L/s.

The measurements were converted to standard air conditions using the procedure described in Section 4.1 .

5.0 INSTRUMENTATION

Instrumentation used in the laboratory program included the following:

Temperature
Temperatures were monitored using thermocouples fabricated from double precision Type "T" wire.

Humidity
Humidity measurements for ambient air were performed using a wet bulb/dry bulb psychrometer.

Atmospheric Pressure
Barometric pressure was monitored using a Taylor Temperature Compensated Barometric Pressure Gauge. A fixed altitude correction was applied to the reading, as the gauge is calibrated to sea level.

Air Pressures
Air pressures (total, static, nozzle static, nozzle differential) were monitored using AIR Instruments Model MP6KD Micromanometers which were individually calibrated against a Dwyer Microtector. Correction factors were applied to the AIR Instrument readings as indicated by the calibration checks, but in no case exceeded 1.3% of the manometer reading.

Rotational Speed
Fan speed was measured using a General Radio Model 1531AB Strobotac.

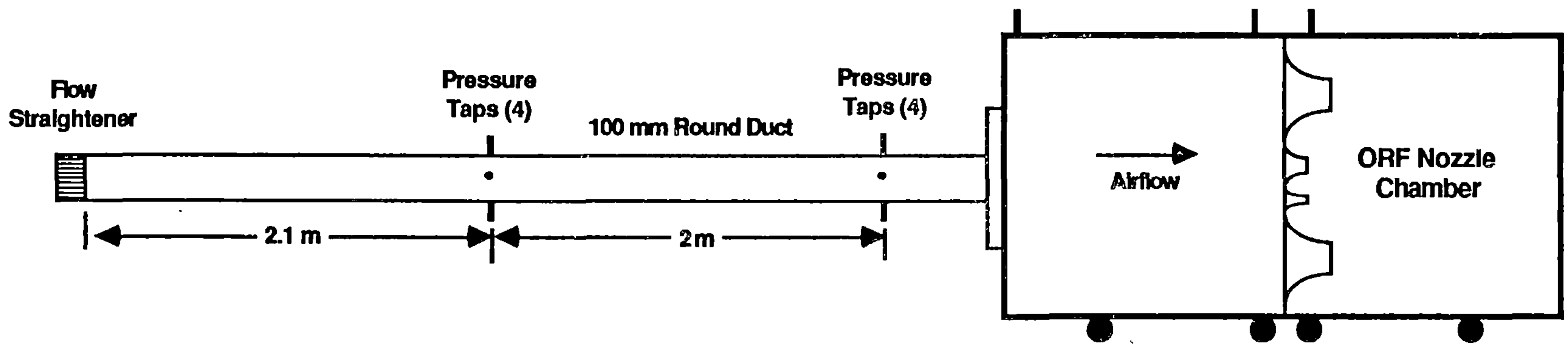


Figure 7: Layout for Pipe Pressure Drop Measurement

6.0 TEST RESULTS

6.1 Pressure Drop Characteristics of Commercial Wall Caps

The pressure drop characteristics of the three wall caps are shown in Figures 8 to 10. In Figure 8, Nutone's data and measurements made by Ontario Hydro from [1] are also shown. Figure 9 also shows Nutone's data for the same wall cap.

6.2 Pressure Drop Characteristics of Commercial Roof Caps

The pressure drop characteristics of the two roof caps are shown in Figure 11 and 12. Also shown on these graphs is Ontario Hydro [1] data for the same roof caps.

6.3 Volume Flow Rates Through Bathroom Exhaust Systems

Table 1 summarizes the volume flow rates and total pressure drops through the various bathroom exhaust system installations. The last column in this table provides an estimate of the leakage in the system between the wall cap and the fan.

6.4 Volume Flow Rates Through Range Hood Exhaust Systems

Table 2 summarizes the volume flow rates and total pressure drops through the various range hood exhaust system installations. As in the case of Table 1, the last column in this table provides an estimate of the leakage in the system between the wall cap and the fan.

6.5 Pressure Drop Through Ducting

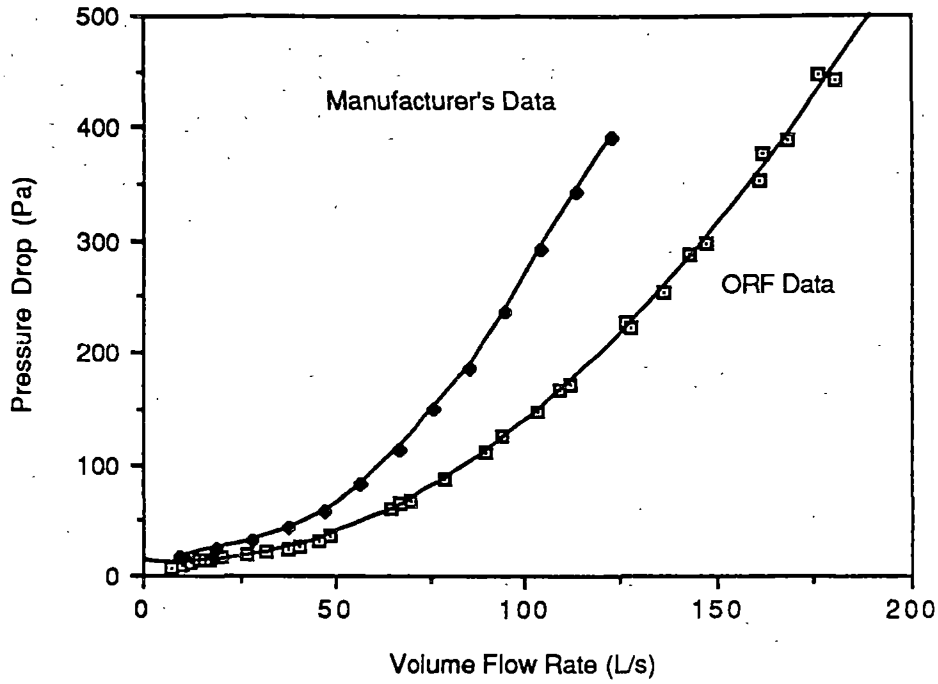
The pressure drop through a 100 mm round duct in presented in Figure 13. Also shown in this graph are the curves from ASHRAE [4] and that predicted by the Blasius equation [5]. The ASHRAE data was obtained for galvanized pipe with 40 slip joints per 30 m while the Blasius equation is an empirical relationship for fully developed turbulent pipe flow in smooth pipes.

7.0 CONCLUSIONS

The following conclusions can be drawn regarding the laboratory measurements of exhaust system components and systems:

- **Pressure Drop Characteristics of Commercial Wall Caps**
  From Figures 8 and 9 it can be seen that the pressure drops measured in these experiments are significantly less than those documented by the manufacturer. The new data is, however, closer to the results originally obtained by Ontario Hydro.

  The Deflecto dryer vent cap is very similar to the bathroom exhaust wall cap. The pressure drop through the Deflecto vent cap was slightly less than that of



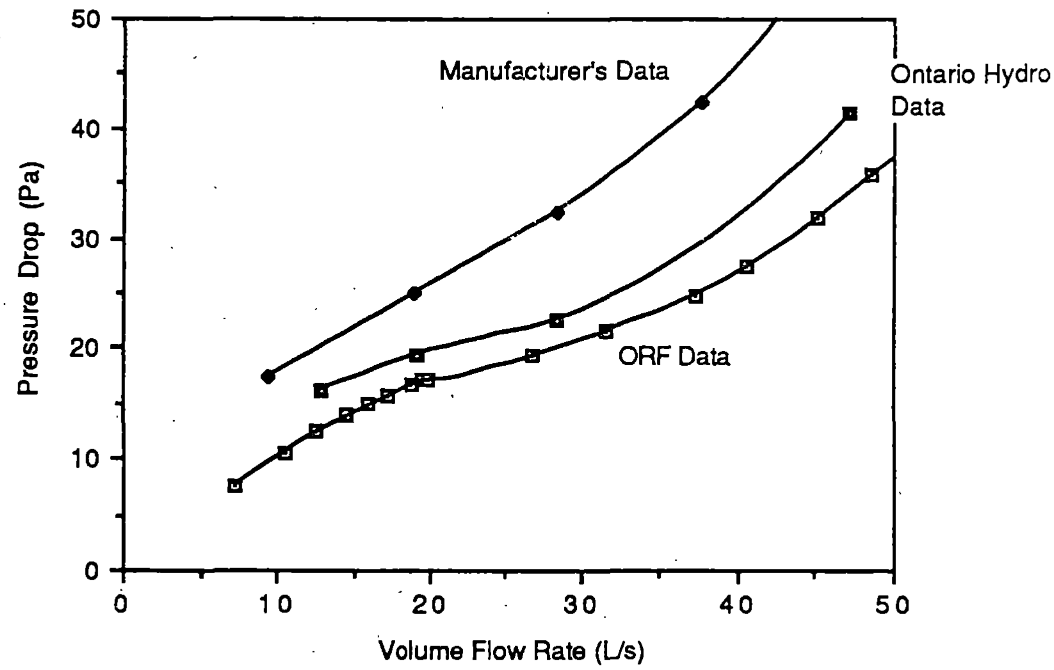


Figure 8: Pressure Drop Characteristic Bathroom Exhaust Wall Cap (100 mm duct)

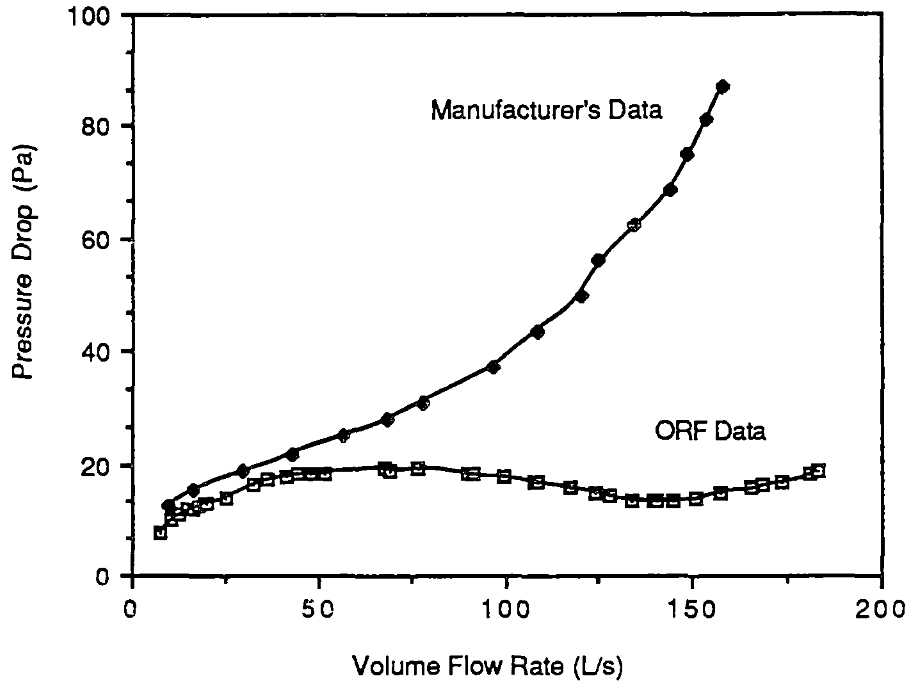
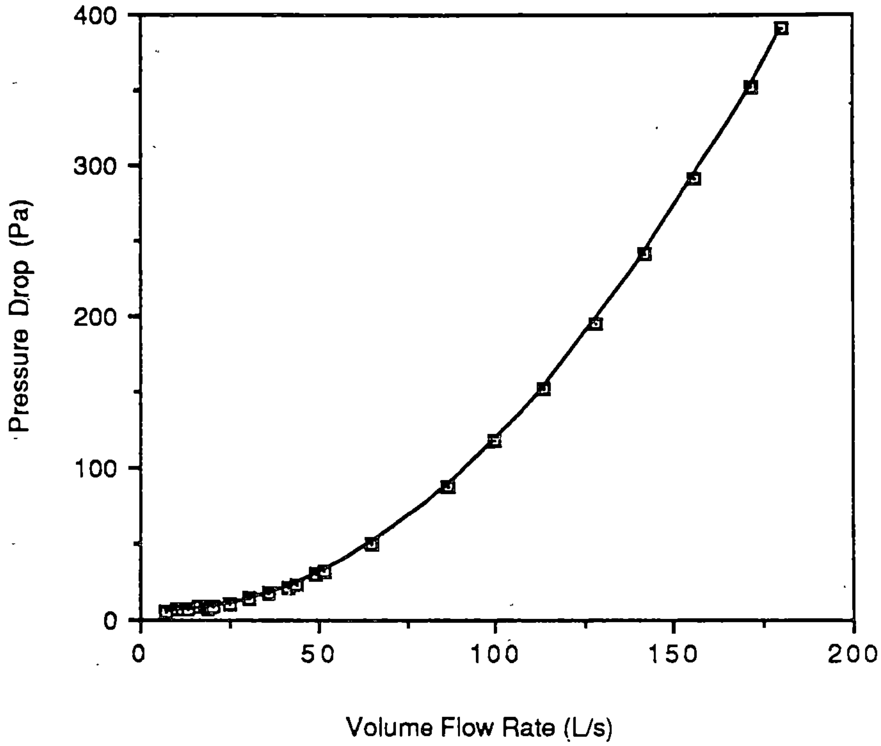


Figure 9: Pressure Drop Characteristic Rangehood Exhaust Wall Cap (rectangular duct)



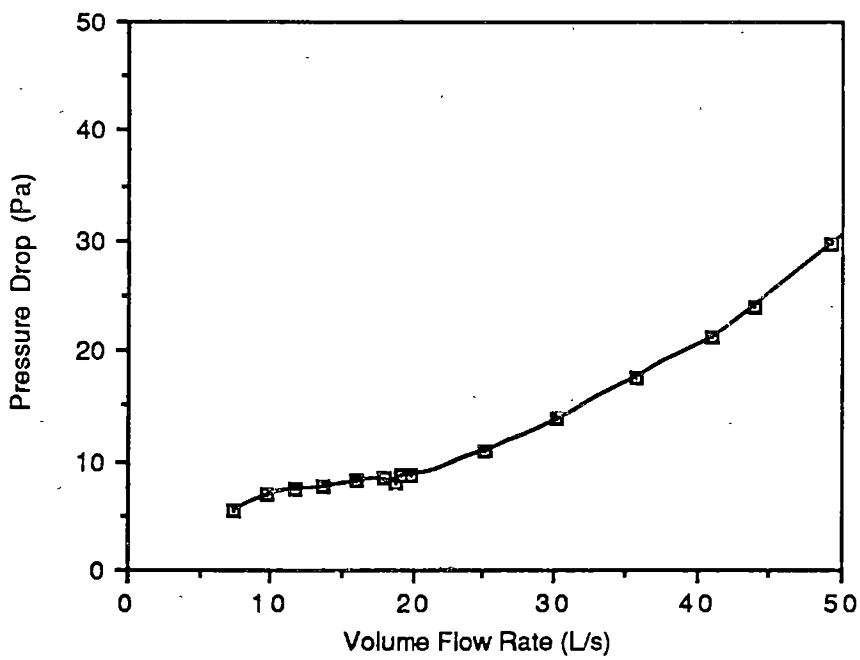
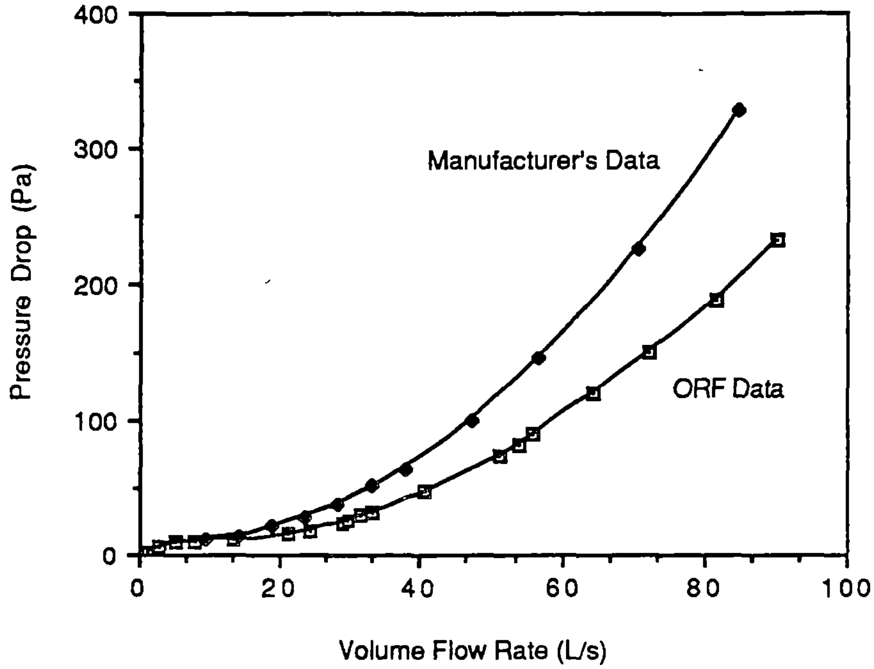


Figure 10: Pressure Drop Characteristic
Deflecto Single Damper Wall Cap (100 mm duct)



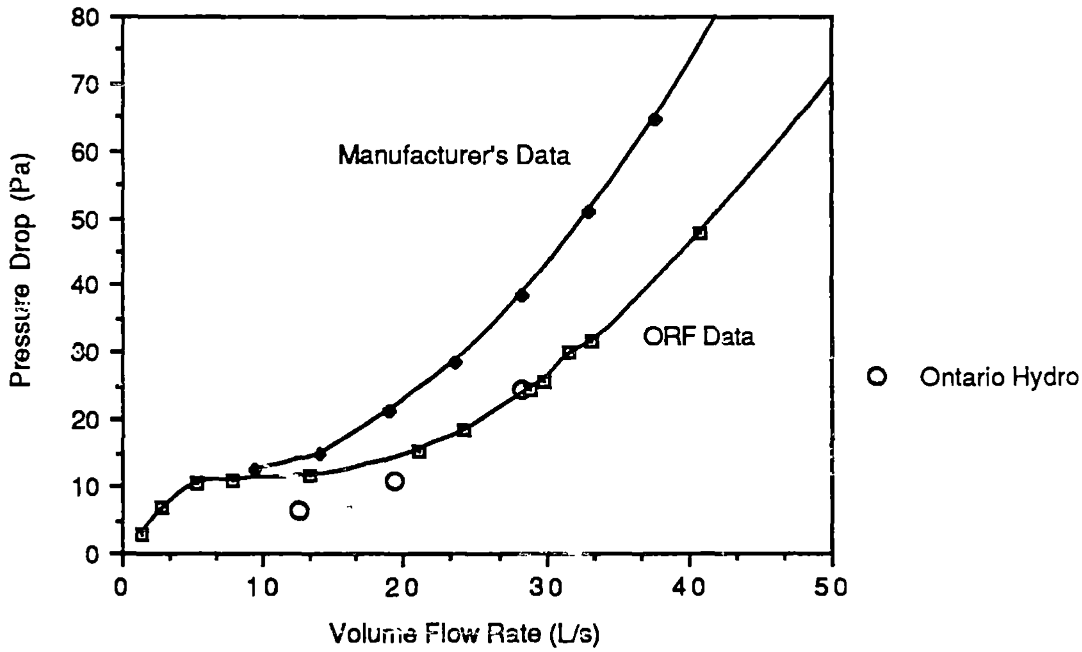


Figure 11: Pressure Drop Characteristic Bathroom Exhaust Roof Cap (100 mm duct)

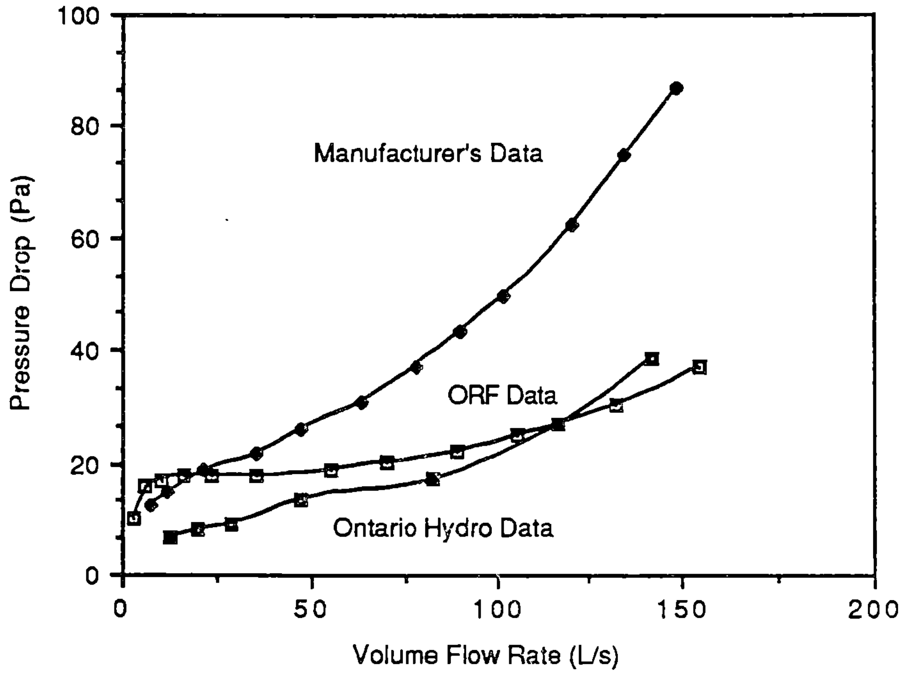


Figure 12: Pressure Drop Characteristic Rangehood Exhaust Roof Cap (rectangular duct)

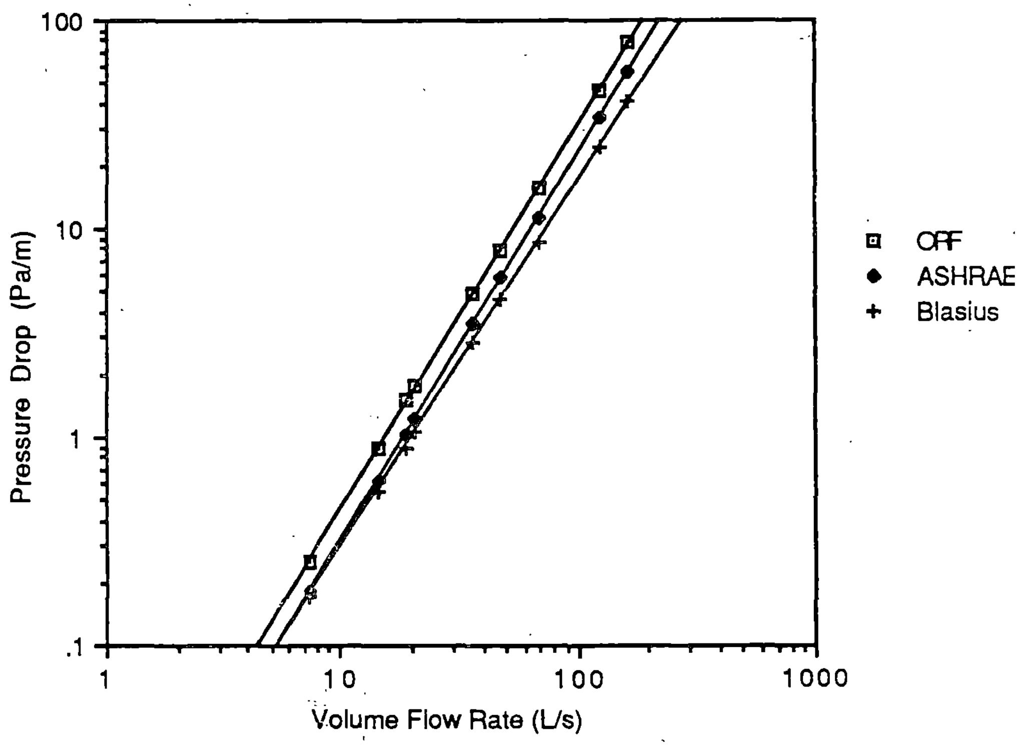


Figure 13: Pressure Drop Through a 100 mm Diameter Duct

the bathroom wall cap. This can be attributed to the absence of a spring in the Deflecto cap, and a larger exit area on the Deflecto cap.

- **Pressure Drop Characteristics of Commercial Roof Caps**
  As with the wall caps, pressure drops measured at ORF are significantly less than those indicated in the manufacturer's data. The Ontario Hydro data is in closer agreement with the new results.

  The large differences existing between the unpublished data provided by the manufacturers and that determined at ORF are difficult to explain. Experimental error could be one explanation. However, the wall and roof caps could have had design changes over the years (eg: return spring changes) which might explain the apparent large differences. However, the Ontario Hydro data would tend to provide evidence that the former reasons cited is a more likely explanation.

- **Volume Flow Rates Through Bathroom Exhaust Systems**
  Table 1 shows a significant reduction in exhaust volume flow rate when the exhaust system is not installed in accordance with manufacturer's instructions. The volume flow rate drops, by about 30 %, in the systems that use 75 mm galvanized duct, rather than 100 mm duct. The type of dryer vent cap does not appear to significantly affect the volume flow rate, in typical installations. Taping the joints does not appear to significantly affect the exhaust flow. The use of the 75 mm flexible duct reduces the volume flow rate by about 50 %.

- **Volume Flow Rates Through Range Hood Exhaust Systems**
  As in the case of the bathroom exhaust systems, Table 2 shows that there is a significant reduction in the volume flow rate when the exhaust system is not installed in accordance with manufacturer's instructions. The use of 100 mm duct rather than the rectangular duct reduces the volume flow rate by about 40% for the systems tested here. Taping joints has a negligable effect on the volume flow rate.

- **Pressure Drop Through Ducting**
  The lowest pressure drops shown in Figure 13 occur for the Blasius equation. This is very likely due to the fact that smooth pipes were used in the experiments that produced this equation. The ASHRAE curve has a higher pressure drop due to the joints and seams in the pipe. The pressure drops, in the experiment reported here, should be higher than those of the ASHRAE data because of the higher number of joints.

  Figure 13 provides an indication of the sensitivity of the duct pressure losses to the number of joints in the pipe.

TABLE 1: VOLUME FLOW RATES AND PRESSURE DROPS THROUGH BATHROOM EXHAUST SYSTEMS

Wall Cap	Duct Size	Comments	Volume Flow Rate Exiting From Cap L/s	Pressure Rise at Fan (obtained from fan speed) Pa	Volume Flow Rate Leaving Fan (obtained from fan speed) L/s	Estimated Leakage L/s
Installation in Accordance with Manufacturer's Instructions						
Manufacturer's Bathroom Exhaust Wall Cap	100 mm	Joints Untaped	28.8 ± 0.5	NA	NA	NA
Manufacturer's Bathroom Exhaust Wall Cap	100 mm	Joints Taped	31.0 ± 0.5	NA	NA	NA
Typical Installation #1						
100 mm Dryer Vent Multi-Damper	75 mm	Joints Untaped	21.3 ± 0.5	62 ± 1.0	28.7 ± 0.2	7.4 ± 0.7
100 mm Dryer Vent Multi-Damper	75 mm	Joints Taped	23.2 ± 0 5	74 ± 1.0	24 7 ± 0.4	1.5 ± 0 9
Typical Installation #2						
75 mm Dryer Vent Single Damper	75 mm	Joints Untaped	20.7 ± 0.5	NA	NA	NA
75 mm Dryer Vent Single Damper	75 mm	Joints Taped	22.0 ± 0.5	73 ± 1.0	25.1 ± 0.3	3.1 ± 0.8
Typical Installation #3						
75 mm Dryer Vent Single Damper	5.5 m of 75 mm Flex Tube	Stretched to 5.1 m	16.0 ± 0.5	91 ± 1.0	18 ± 0.5	1.6 ± 1.0
75 mm Dryer Vent Single Damper	7 m of 75 mm Flex Tube	Stretched to 5 7 m	13.7 ± 1.0	96 ± 1.0	15 ± 0.6	1.2 ± 1.6

TABLE 2: VOLUME FLOW RATES AND PRESSURE DROPS THROUGH RANGEHOOD EXHAUST SYSTEMS

Wall Cap	Duct Size	Comments	Volume Flow Rate Exiting From Cap L/s	Pressure Rise at Fan (obtained from fan speed) Pa	Volume Flow Rate Leaving Fan (obtained from fan speed) L/s	Estimated Leakage L/s
Installation in Accordance with Manufacturer's Instructions						
Manufacturer's Rangehood Exhaust Wall Cap	83 x 255 mm	Joints Taped	86 ± 1.5	50 ± 4	90 ± 1.9	4 ± 3.4
Typical Installation						
100 mm Dryer Vent Single Damper	100 mm	Joints Untaped	52 ± 1 0	133 ± 5	52 ± 2.8	0 ± 3.8
100 mm Dryer Vent Single Damper	100 mm	Joints Taped	52 ± 1.0	137 ± 5	50 ± 3 0	-2 ± 4.0

NA: not available

8. REFERENCES

[1] CSA Standard C260.1-1975, "Installation Code for Residential Mechanical Exhaust Systems", Canadian Standards Association, December 1975

[2] ASHRAE 1985 Fundamentals, American Society of Heating Refrigerating and Air-Conditioning Engineers Inc., Atlanta GA, pp 33.8

[3] "Air Delivery Capabilities of Residential Range Hoods and Bathroom Exhausters", Energy Systems Centre, Ontario Research Foundation, Final Report, ES/ESC-87-109, October 6, 1987

[4] ASHRAE 1985 Fundamentals, American Society of Heating Refrigerating and Air-Conditioning Engineers Inc., Atlanta GA, pp 33.26

[5] Schlichting H., "Boundary Layer Theory", McGraw-Hill, New York, 1968, pp 561

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APPENDIX I

ORF NOZZLE CHAMBER

The ORF nozzle chamber is a facility for measuring volume flow rate of air through ducts, blowers, transitions, elbows and other duct components. The facility is based on specifications given in AMCA Standard 210-74 "Laboratory Methods of Testing Fans for Rating". A diagram of the chamber is provided in Figure I.1 .

The volume flow rate through the inlet is obtained by measuring the pressure drop across the nozzles, the static pressure at the nozzle inlets, the dry bulb temperature and wet bulb temperature. These measurements are applied to equations provided in AMCA 210-74 which give the volume flow rate.

The nozzle chamber has been checked against a calibrated Laminar Flow Element. Measurements by the two devices have been found to differ by less than 1.5 % over the flow range covered in this report.

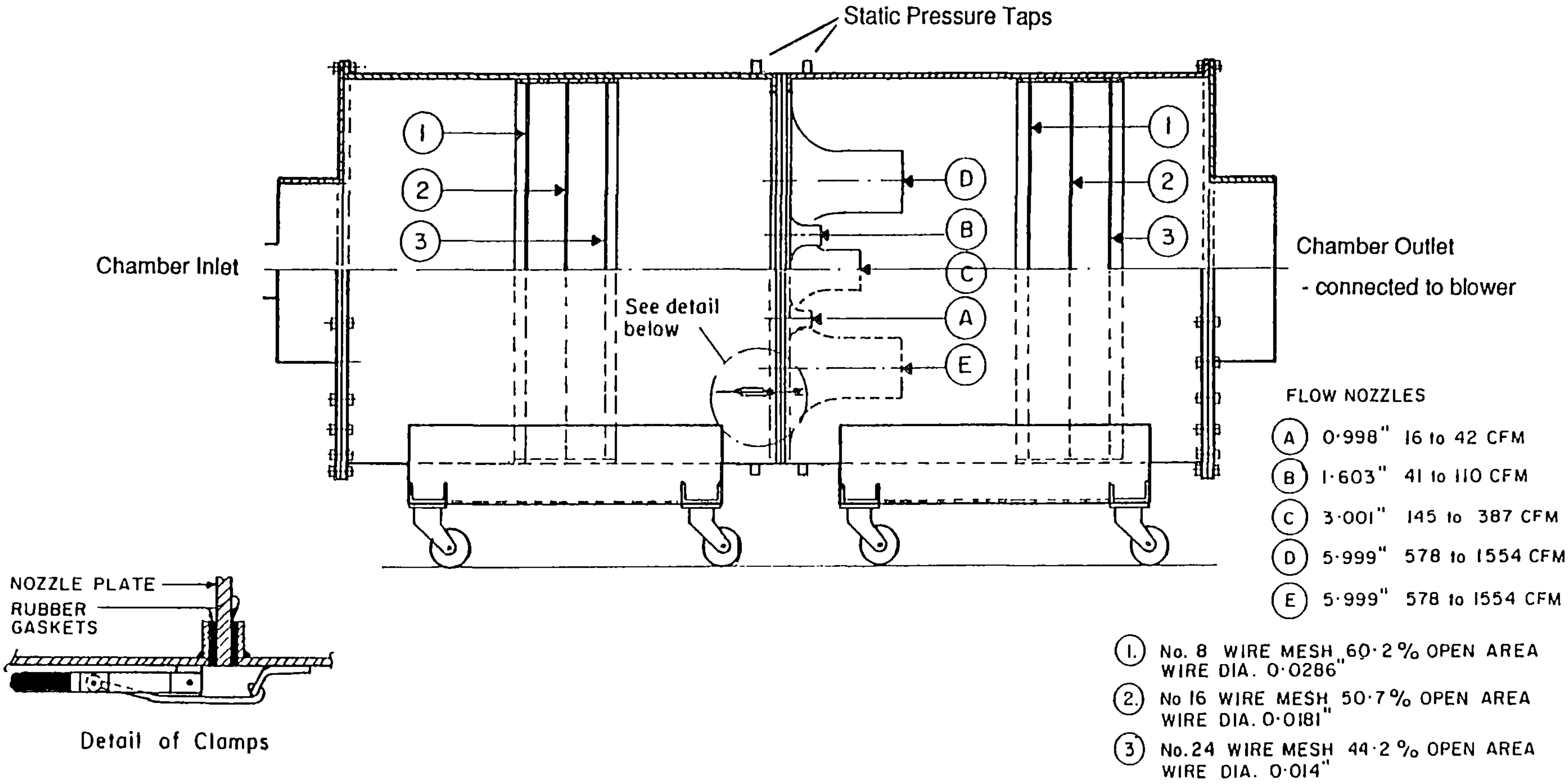

Figure I.1: ORF Airflow Test Nozzle Chamber