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Bass Abushakra, Iain S. Walker,
and Max H. Sherman

**Environmental Energy
Technologies Division**

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A Study of Pressure Losses in Residential Air Distribution Systems

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ABSTRACT

An experimental study was conducted to evaluate the pressure drop characteristics of residential duct system components that are either not available or not thoroughly (sometimes incorrectly) described in existing duct design literature. The tests were designed to imitate cases normally found in typical residential and light commercial installations. The study included three different sizes of flexible ducts, under different compression configurations, splitter boxes, supply boots, and a fresh air intake hood. The experimental tests conformed to ASHRAE Standard 120P – *Methods of Testing to Determine Flow Resistance of HVAC Air Ducts and Fittings*. The flexible duct study covered compressibility and bending effects on the total pressure drop, and the results showed that the available published references tend to underestimate the effects of compression in flexible ducts that can increase pressure drops by up to a factor of nine. The supply boots were tested under different configurations including a setup where a flexible duct elbow connection was considered as an integral part of the supply boot. The supply boots results showed that diffusers can increase the pressure drop by up to a factor of two in exit fittings, and the installation configuration can increase the pressure drop by up to a factor of five. The results showed that it is crucial for designers and contractors to be aware of the compressibility effects of the flexible duct, and the installation of supply boots and diffusers.

Introduction

The installation of air distribution systems and the type of duct fittings used play a major role in the overall system performance. It is crucial for the designer and the contractor to realize the impact pressure drop in flexible ducts and fittings can have on the power consumption and the overall performance of the HVAC system. To satisfy the ARI 210/240 requirements for minimum external pressure on indoor air-moving equipment, a proper estimate of pressure drops in the air-distribution system is critical. Proctor and Parker (2000) noted that the measured external static pressure in seven field tests (245 north American houses) were two to four times higher than the standard DOE assumptions. Pressure losses in an air distribution system are balanced by pressure increases at the installed fan. It is very important that every feasible means be used to control the fan power use. Increased flow resistance in the ducts results in increase in pressure drop, therefore lower airflow. This leads to increased fan power use and a lower heat exchanger efficiency (due to a lesser capacity). The combination of these effects can significantly increase power and energy consumption. Designing and properly installing duct systems that are energy efficient is therefore instrumental in achieving an overall energy efficient HVAC system. The available literature lacks sufficient description of pressure losses in flexible ducts and loss coefficients for other commonly used residential duct fittings such as, splitter boxes, outside air intake hoods and air supply boots.

In this study, laboratory testing and a detailed analysis of airflow and resistance were conducted by the Energy Performance of Buildings Group at LBNL. This was done to identify key aspects of the performance of air distribution systems with commonly used fittings so that these systems can be improved in both new construction and retrofits of existing buildings. The

analysis was divided in two parts, the *component analysis* and the *complete duct system analysis*. A full-scale residential air distribution system testing facility was built to perform the *complete duct system analysis*. The laboratory measurements allowed the evaluation of the flow resistance parameters of duct fittings under controlled conditions following standard procedures (ASHRAE Standard 120P "Methods of Testing to Determine Flow Resistance of HVAC Air Ducts and Fittings"(1995)), in addition to the performance of a controlled and complete full-scale air distribution system. The work is described in more detail in Abushakra et al. (2002).

Methodology

The test objectives were to measure the pressure drop in various residential duct components and expressing the results in terms of power law coefficients for straight ducts, and local loss coefficients for the fittings. The test procedures were based on proposed ASHRAE Standard 120P and involved different lengths of sheet metal duct sections installed upstream and downstream of the test specimens, air moving fans, airflow measuring devices, and data loggers and hand-held manometers. As required by ASHRAE Standard 120P, piezometer rings, the same diameter as the test ducts, were used that each have four equidistant static pressure taps for upstream and downstream pressure measurements. Airflows were measured using either a 6" (150 mm) nozzle flowmeter ($\pm 0.5\%$ of reading accuracy) or a combined fan/flowmeter device with $\pm 3\%$ accuracy. Flow straighteners that reduce swirl and turbulence were incorporated into the experimental apparatus and the flow meters. For the splitter box tests a fan/flowmeter was mounted on each downstream leg of the splitter boxes to suck air through the test system and measure the flow through each leg. The 6" (150 mm) nozzle flowmeter was used to measure the total airflow through the main branch upstream of the splitter box. All pressure and flow measurements were averaged for five seconds and the readings were recorded using a data logger. In addition to the data loggers, hand-held electronic digital pressure gauges were used in the supply boot and the splitter box tests to modulate different pressure/flow stations. The experimental results were corrected for temperature changes during the test and for changes in flowmeter calibrations with temperature. Also elevation corrections were made because some of the tests were performed at sea level and others at several hundred feet elevation. Throughout the tests, the volumetric flow rate ranges were those that are encountered in typical residential systems. The results of the component analysis were compared with available references, whenever a similar duct fitting was reported in the literature. A further evaluation of the components analysis results was performed through a comparison with measured pressure drop in an installed air distribution system.

Component Analysis

The flexible duct tests were performed on 6", 8" and 10" (150, 200 and 250 mm) diameter samples. The flexible duct consists of three layers: (1) outer plastic layer, (2) R-4.2 (RSI-0.74 m^2K/W) fiberglass insulation, and (3) inner liner which is a thin plastic layer with embedded spiral wire. The samples were tested with three compression configurations (where the compression ratio is the change in length divided by the fully stretched length): fully stretched, a natural stretch configuration (15% compression), and compressed (30% compression). These compression values are somewhat arbitrary, but the rationale for the selected values was as follows: the fully stretched has the inner core of the flexible duct pulled tight resulting in a relatively smooth inner duct surface (this is rarely found in houses, because it results in ducts which are hard to keep on the fittings). Above the 30% compression ratio, it was

not possible to keep the compressed specimen straight, because of bulging caused by restrictions due to the outer liner and the insulation of the flexible duct.

Fully stretched (FS) flexible ducts were tested first in order to establish a baseline for all compression scenarios. The pressure drop in the flexible duct, was characterized as a function of the flow rate using the power law model (Equation 1), that allows for variations (for instance, due to boundary layer development for Reynolds Number effects) from the standard assumption of volumetric flow rate being proportional to the square root of the pressure drop:

$$\Delta P = CQ^n \quad (1)$$

The fully stretched specimen length was at least 35 diameters, satisfying the minimum 25-diameter-length suggested by Standard 120P for fully developed flow. A 35-diameter-length specimen can be compressed by as much as 30% and still satisfy the 25-diameter overall length constraint. Figure 1 shows the test specimens of the fully stretched and compressed 10" (250 mm).

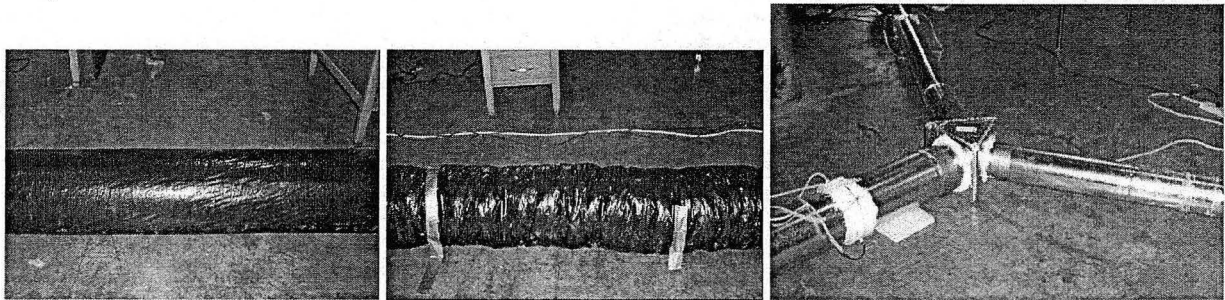


Figure 1. Stretched and compressed 10" (250 mm) flexible duct and splitter box test specimens.

Three flexible duct elbow angles were tested of 45°, 90° and 135°. Each of the elbow configurations included a natural stretch and a compressed configuration. The total number of flexible duct tests conducted for each duct size was nine, totaling 27 tests for all three duct sizes.

The splitter boxes tests (Figure 1) were performed using three sizes: 10"x8"x6" (250x200x150 mm), 10"x8"x8" (250x200x200 mm), and 8"x6"x6" (200x150x150 mm). The three numbers refer to the inlet diameter and the two outlet diameters respectively. The pressure drops and loss coefficients were determined separately for each splitter box branch. This required a piezometer be placed on each individual branch together with fans to control the amount of flow in each branch. These two fans are also used as flow measuring devices. A nozzle flowmeter was attached to the main leg of the splitter box, and acted as a check on the total flow from the two branches. The standard method of reporting local loss coefficients for diverging and converging junctions is the flow rate ratio (branch-to-main) and the corresponding loss coefficient through that branch. Pressure/flow stations were uniformly designed so that the flow rate ratio changed in approximately equal steps between 0 and 1.

Three types of supply boots were tested: 8" (200 mm) diameter neck Angle Supply, 8" (200 mm) Straight Supply, and 6" (150 mm) Straight Supply. The angle supply boot was tested while connected to a horizontally spanning sheet metal duct. The straight supply boots were tested under three different configurations: straight supply with a sheet metal duct, and connected to a flexible duct forming a 90° elbow in two orientations: *Angle 1* is when the boot is fed from the duct along the axis of its narrow dimension, and *Angle 2* is when the boot is fed from the duct along the axis of its wide dimension. Each of the supply boots was mounted on a wooden wall and tested without a diffuser and with a diffuser added to assess the additional pressure drop that

can be encountered in an actual installation. Thus a total number of 14 tests were conducted to study the supply boots. Figure 2 shows the various configurations of the supply boots tests.

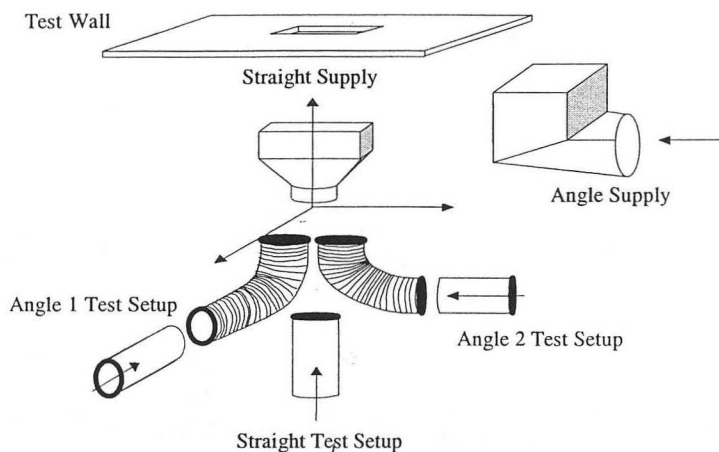


Figure 2. Different configurations of connecting the supply boots to the supply duct as used in the tests, including the attachment to a wall, with and without diffuser.

The final component tested was an air intake hood, mounted on a wooden wall. The hood has a square entry and draws air parallel to the wall, through a screen. The airflow then makes a 90° turn inside the hood and exits it through a round 8” (200 mm) exit.

Results of Component Analysis

Tables 1 to 7 summarize the results of the component analysis in terms of tests flow conditions, power law coefficients for the flexible duct, and local loss coefficients for the flexible duct elbows, supply boots, splitter boxes and the air-intake hood. The local loss coefficients are calculated as the ratio of the total pressure to the velocity pressure across a fitting.

TABLE 1. Flow Conditions in the Flexible Duct Tests

Nominal Diameter inch (mm)	Compression Scenario	Compression Ratio r_c (%)	Reynolds Number Range
6 (150)	Fully Stretched	0.0	24,000 – 115,000
	Natural Stretch	13.8	22,000 – 108,000
	Compressed	28.6	23,000 – 104,000
8 (200)	Fully Stretched	0.0	21,000 – 97,000
	Natural Stretch	14.6	21,000 – 95,000
	Compressed	23.8	23,000 – 94,000
10 (250)	Fully Stretched	0.0	25,000 – 73,000
	Natural Stretch	14.8	22,000 – 73,000
	Compressed	29.5	21,000 – 75,000

TABLE 2. Flow Conditions in the Residential Duct Fittings Tests

Fitting	Size inch (mm)	Volumetric Flow Rate cfm (L/s)	Velocity fpm (m/s)
Bent Flexible Duct (Elbows)	6 (150)	80 – 390 (40 – 180)	420 – 2000 (2 – 10)
	8 (200)	100 – 440 (50 – 210)	300 – 1250 (1.5 – 6)
	10 (250)	360 – 530 (170 – 250)	650 – 970 (3 – 5)
Splitter Boxes	8x6x6 (200x150x150)	150 (70)	430 (2)
	10x8x8 (250x200x200)	300 (140)	550 (3)
	10x8x6 (250x200x150)	225 (110)	410 (2)
Supply Boots	6 (150)	25 – 140 (10 – 70)	130 – 730 (1 – 4)
	8 (200)	50 – 280 (20 – 130)	145 – 800 (1 – 4)

TABLE 3. Power Law Coefficients of Three Sizes of Flexible Ducts and Comparison with Resulting Pressure Drop with Available References

Nominal Diameter Inch (mm)	Compression Ratio r_c (%)	C inch water/ 100 ft. cfm ⁿ (Pa.s ⁿ /m.L ⁿ)	n	ACCA-ASHRAE Pressure Drop* Average Over/Under-prediction
6 (150)	0.0	1.20 E-05 (2.08 E-04)	1.98	+11%
	13.8	6.04 E-05 (1.05 E-03)	1.94	-28%
	28.6	1.56 E-04 (2.70 E-03)	1.90	-47%
8 (200)	0.0	3.33 E-06 (5.76 E-05)	1.90	+39%
	14.6	8.13 E-06 (1.41 E-04)	1.99	-8%
	23.8	1.71 E-05 (2.96 E-04)	1.94	-14%
10 (250)	0.0	7.31 E-07 (1.27 E-05)	1.99	+13%
	14.8	2.75 E-06 (4.76 E-05)	1.98	-15%
	29.5	4.53 E-06 (7.84 E-05)	1.97	-12%

* ACCA-ASHRAE values are average values of pressure drop corresponding to the flow rates used in each test, and calculated by multiplying the look-up values in ACCA Manual D Chart 7, page A2-10 (ACCA 1995) by the correction factor in ASHRAE Fundamentals (ASHRAE 2001), Figure 8, p.34.8. For the fully stretched case (0% compression) the correction factor is 1.

TABLE 4. Results of the Bent Flexible Duct Tests

Diameter inch (mm)	Bending Angle θ °	Compression Ratio r_c (%)	Elbow Length L inch (mm)	Radius-to- Diameter Ratio r/D	Local Loss Coefficient K
6 (150)	90	5.0	19 (480)	2.50	1.18
		18.6	50 (1270)	5.00	3.27
	45	4.8	46 (1170)	9.67	1.76
		24.3	36 (915)	4.00	3.13
	135	4.8	30 (760)	1.83	1.90
		30.5	24 (610)	1.67	3.12
8 (200)	90	13.6	36 (915)	2.00	2.85
		34.2	35 (890)	2.50	2.31
	45	11.8	34 (85)	2.75	2.26
		30.5	22 (560)	2.38	1.85
	135	7.7	36 (915)	2.38	2.84
		33.1	32 (815)	2.00	2.54
10 (250)	90	6.9	63 (1600)	4.20	1.73
		35.8	41 (1040)	2.70	1.35
	45	4.8	54 (1370)	6.80	1.15
		33.6	24 (610)	3.80	0.87
	135	5.0	69 (1750)	2.20	1.55
		33.8	39 (990)	1.40	1.45

TABLE 5. The 10''x8''x6'' (250x200x150 mm) Splitter Box Local Loss Coefficients

$D_1 = 10'' (250 \text{ mm}), D_2 = 6'' (150 \text{ mm}), D_3 = 8'' (200 \text{ mm})$							
Q_3/Q_1	0.00	0.18	0.33	0.49	0.67	0.82	1.00
$K_{1,3}$	-	6.34	2.58	1.94	1.48	1.15	0.87
Q_2/Q_1	1.00	0.82	0.67	0.51	0.33	0.18	0.00
$K_{1,2}$	0.63	0.68	0.82	0.88	1.03	1.91	-

TABLE 6. The 10''x8''x8'' and 8''x6''x6'' (250x200x200 and 200x150x150 mm) Splitter Boxes Local Loss Coefficients

$D_m = 10'' (250 \text{ mm}), D_b = 8'' (200 \text{ mm})$					
Q_b/Q_m	0.00	0.27	0.50	0.73	1.00
$K_{m-b, \text{average}}$	-	4.00	1.45	0.85	0.63
$D_m = 8'' (200 \text{ mm}), D_b = 6'' (150 \text{ mm})$					
Q_b/Q_m	0.00	0.27	0.50	0.73	1.00
$K_{m-b, \text{average}}$	-	3.08	1.11	0.71	0.61

TABLE 7. Local Loss Coefficients of Various Configurations of the 8'' (200 mm) Neck Diameter Angle Supply, and the 8'' and 6'' (200 and 150 mm) Neck Diameter Straight Supply Boots

Type	Boot Neck Diameter inch (mm)	Flexible Duct Section			Setup	Local Loss Coefficient K	
		Length inch (mm)	Radius inch (mm)	Compression Ratio r_c (%)		With Diffuser	Without Diffuser
Angle Supply	8 (200)	-	-	-	-	2.43	1.23
Straight Supply	8 (200)	19 (480)	13 (330)	45.7	Angle 1	3.86	3.03
		-	-	-	Angle 2	3.77	2.87
		-	-	-	Straight	1.76	1.02
	6 (150)	21 (530)	14 (355)	19.0	Angle 1	5.31	4.61
		-	-	-	Angle 2	4.57	4.28
		-	-	-	Straight	1.30	0.98

Discussion of Component Analysis

Effect of Compression on Pressure Loss in Flexible Ducts

In field studies, observed pressure drops in flexible duct systems are often higher than expected based on design calculations. This is because the flexible ducts are often found to be compressed to varying degrees. This common problem leads to excessive pressure drop in many systems, with associated fan power, flow restriction and noise issues. For design purposes and for diagnosing duct systems, engineers and analysts consult friction charts and matching friction loss coefficients from references. For fully stretched flexible duct, in particular, ASHRAE Fundamentals (ASHRAE 2001) and ACCA Manual D (ACCA 1995) provide pressure drop calculations. However, when it comes to the compression effects on flexible ducts, the available literature does not provide enough resources for a good estimate of pressure drop in a duct system. ASHRAE Fundamentals provides a graph, showing how compressing a fully stretched flexible duct increases the pressure drop. This single graph is used for all sizes of flexible ducts, and there is no friction chart provided.

ASHRAE Fundamentals (ASHRAE 2001) suggests the use of the friction loss equation with the Altshul-Tsal equation of friction factor (Altshul and Kiselev 1975, and Tsal 1989), for the calculation of pressure drop in flexible ducts: The problem with using ASHRAE friction

drop equations is in estimating the correct value of the absolute roughness, because roughness data for flexible ducts are generally not available. ASHRAE Fundamentals categorizes the roughness in five categories (smooth, medium-smooth, average, medium-rough, and rough) and provides a general absolute roughness value for each category. It also provides a range for the roughness of each type of duct in each category. Flexible duct, "all types of fabric and wire", are considered medium-rough to rough, with an absolute roughness range of 0.0035-0.015 ft (1.0-4.6 mm) when fully extended. No guidance is provided to select values corresponding to different compression ratios.

When the flexible duct is compressed, the inner surface gets crumpled and the effective surface roughness increases orders of magnitude above the range provided in ASHRAE Fundamentals. For the designer, even using an appropriate model for the friction factor and surface roughness, would be problematic since having the appropriate value of the roughness for the specific compression case of the flexible duct is not available.

ACCA Manual D (ACCA 1995) provides a friction chart for flexible, spiral wire helix core ducts. There are conditions for using the chart, such as maximum air velocity and temperature and positive and negative pressure, but there is no indication of whether the chart was established for "fully extended" ducts. No references are available from ACCA to determine the source of the ACCA data. To compare our results with the available references, the values provided by ACCA were multiplied by the correction factors provided in ASHRAE (2001). The ACCA chart overpredicted the pressure drop for the fully stretched duct of all sizes tested, on an average, by 21%. This indicates that ACCA Manual D data was probably obtained from partially compressed flexible duct. ACCA underpredicted the pressure drop by 17% for the normal stretch cases, and by 24% for the compressed cases (around 30% compression). The results of compressed ducts also showed that when a flexible duct is compressed, it could have a greater pressure drop per unit length than a fully stretched duct of a smaller diameter.

Other researchers that have recently studied the effects of compression on flexible duct pressure drops (IBACOS (1995) and Kokayko et al. (1996)) gave some results close to ours but in other cases there were substantial differences and inconsistencies from one duct size to another. Unfortunately, these reports do not give enough detail regarding measurement procedures and subsequent analysis to discuss the similarities and differences in detail.

Development of a Pressure Drop Correction Factor

The pressure drop correction factor (*PDCF*) is a multiplier that can be used to estimate the pressure drop in a flexible duct when less than fully stretched, based on the pressure drop of a fully stretched duct:

$$PDCF = \frac{\Delta P}{\Delta P_{FS}} \quad (2)$$

where ΔP is the pressure drop at a particular level of compression, and ΔP_{FS} is that corresponding to a fully stretched configuration. Analysis of the measured data has shown that the pressure drop correction factor, *PDCF*, is approximated well by a linear function of the compression ratio, r_c . The compression ratio, r_c , is calculated from measuring the length of the test specimen, fully stretched and under compression. The compression ratio is the change in length divided by the fully stretched length, such that:

$$PDCF = 1 + ar_c \quad (3)$$

where *PDCF* would be equal to 1 (no correction) for a zero compression. The empirical coefficient, a , can be obtained from the experimental data for each duct size using:

$$a = \frac{\sum_{j=1}^m \left(\frac{\sum_{i=1}^n \frac{\Delta P}{\Delta P_{FS}}}{n} - 1 \right)}{\sum_{j=1}^m r_c} \quad (4)$$

where: n = number of volumetric-flow-rate/pressure-drop stations in a test,
 m = number of compression cases (tests) including the fully stretched case.

TABLE 8. Pressure Drop Correction Factor of Three Sizes of Flexible Duct

Diameter, inch (mm)	Pressure Drop Correction Factor, PDCF
6 (150)	$1 + 25.4 r_c$
8 (200)	$1 + 21.6 r_c$
10 (250)	$1 + 16.2 r_c$
ASHRAE-all sizes	$1 + 9.9 r_c$

Table 8 shows the *PDCF* models developed using Equation 3. A reference model, *ASHRAE-all sizes*, is also listed for comparison. This reference model was obtained with a best-fit first order polynomial ($PDCF = 1 + 9.9 r_c$), developed from the look-up values from ASHRAE (2001). The ASHRAE model is independent of duct size and underestimates the pressure drop by an average of 35% compared to our measured data.

Rather than have multiple equations for calculating *PDCF* we examined the possibility of collapsing the results to single relationship using duct geometry factors. The physical basis of the empirical relationship for the *PDCF* (Equation 3) can be explained in terms of change in the friction factor and the geometry of the flexible duct when compressed. Compressing the flexible duct results in a crumpled inner liner which reduces the effective interior cross-sectional area and increases its absolute surface roughness. The pitch, λ , is the distance between two consecutive spirals of flexible duct. The degree of area reduction and roughness increase depends on the pitch-to-diameter ratio (larger pitch leads to higher cross-sectional area changes and greater roughness). Dividing our measured values of a by the corresponding pitch-to-diameter ratio of the fully stretched duct, λ_{FS}/D_{FS} , generated values that are approximately equal, with an average value of 106. The use of this single value had differences of less than 5% compared to all the measured points. It is possible that this relationship could be used for ducts of other diameters and pitches, but tests on other ducts need to be carried out in order to confirm this. The pitch-to-diameter-normalized *PDCF* values use the following expression:

$$PDCF_{Norm} = 1 + 106 \left(\frac{\lambda_{FS}}{D_{FS}} \right) r_c \quad (5)$$

Bent flexible duct. The flexible duct elbows results are expressed in the form of local loss coefficients. The loss coefficients increase with increasing turn angle, but no systematic variation can be seen. This is because of the geometry effects of varying compression ratios and the ratio of bend radius to duct diameter. The more compressed ducts do not always have higher loss coefficients for the same reason. The only similar data reported in the literature, that can be used to compare our results of the bent flexible duct were in ACCA Manual D, IBACOS (1995),

and in a flexible duct manufacturer product literature. ACCA Manual D provides effective length (EL) values for elbows independent of duct size, and radius to diameter ratio (r/D). IBACOS (1995) showed the static pressure loss for 8" (200 mm) 135° and 90° elbows with three radius-to-diameter ratios. The pressure losses reported convert to local loss coefficients ranging between 2.49 and 3.93, which covers the range of our results. The manufacturers brochure showed values of local loss coefficient for a 12" (305 mm) diameter 90° elbows that ranged between 0.82 and 0.86 for radius-to-diameter ratios between 1.0 and 4.0. These results are somewhat consistent with our results for smaller duct diameters (local loss coefficient decreasing as the duct diameter increases). Our results showed that flexible duct elbows have much higher local loss coefficients than those reported for sheet metal elbows in the literature (ASHRAE 2001). The local loss coefficients for multiple gores and pleated sheet metal elbows in ASHRAE (2001) are all below 1.0, for different angles, and r/D configurations of 2.5 and below. The higher loss coefficients values observed in the flexible duct elbows can be explained by the increased absolute surface roughness of the compressed flexible duct compared with that of the sheet metal elbows.

Splitter Boxes. ASHRAE Fundamentals shows local loss coefficients values for rectangular "Tee's" and "Wye's" that cover the range of the results obtained in this study. However, ASHRAE Fundamentals does not show data for splitter boxes. ACCA Manual D provides pressure drop for splitter boxes, in terms of equivalent length (EL), independent of size (main and branches). For an air velocity of 700 fpm (3.6 m/s), ACCA's splitter box EL value corresponds to a static pressure value of 0.08 in water (19.9 Pa), compared with a total pressure value of 0.045 in water (11.2 Pa) based on our calculated loss coefficients (for the larger branch of the 10"x8"x6" splitter box, assuming a 0.67 flow rate ratio). The values in ACCA Manual D, therefore, overestimate the pressure drop in splitter boxes compared to our test results.

Supply Boots. The supply boots results showed that diffusers have a major effect on the pressure losses in exit fittings. The diffuser increases the loss coefficient by factors between 1.1 and 2.0, depending on the configuration of the boot connection. For added flexible duct cases, the pressure drop increased by factors between 3 and 4, compared with the figures obtained when the boot is connected to a straight sheet metal duct. ACCA Manual D provides equivalent length values for supply boots, and includes a value for a supply boot having a flexible elbow attached to it. Our test results show that ACCA Manual D values underestimate the static pressure drop in the boots by about a factor of 3.

Air-intake hood. The local loss coefficient of the intake hood was 4.1; a substantial factor in the pressure drop to be considered when designing the ducting system. A similar hood could not be found in the literature for a comparison. ASHRAE Fundamentals indicates that a screen (only), having the exact size of the ducted inlet has a loss coefficient between 0.0 and 6.2, depending on the free area ratio of the screen. ASHRAE Fundamentals 2001 gives a loss coefficient value of 0.5 (duct flush with wall) for a "Duct Mounted in Wall". ACCA Manual D does not include outside air-intake hoods.

Evaluation of Results with a Complete Duct System Analysis

The second part of the study applied the individual component analyses to a complete duct system to check that the individual components can be combined to produce the same

system pressures as a fully assembled complete system. A complete full-scale residential air distribution system was built in the Energy Performance of Buildings Group Duct Lab. This duct system was designed to be representative of duct systems found in California houses and is based on a survey of 20 homes (part of this study). The system had two supply branches (A and B) out of the supply plenum, and had 11 supply registers and a single return, with a total system flow of 1,200 cfm (566 L/s). Its layout and other details are shown in Figure 3. All duct runs were as straight as possible and the ducts were cut to the correct length so as not to compress the ducts. The average compression ratio in all the flexible duct runs was 10%. The ducts are hung below a plywood deck, with the register boots attached to the underside of the deck. The system was carefully sealed and its leakage measured using a pressurization test was only 9 cfm (4 L/s) at 25 Pa.

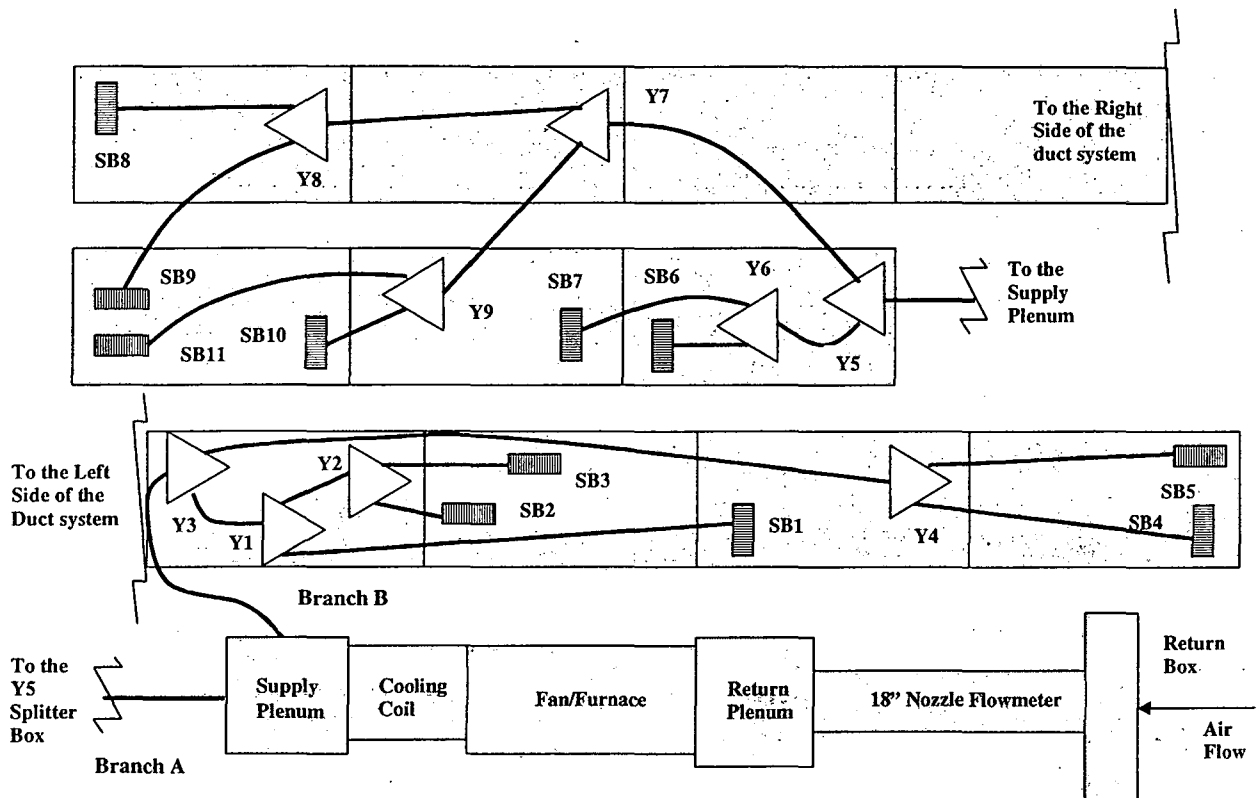


Figure 3. Layout of the complete residential air distribution system built for the study.

The airflow was measured at every register using a powered flow hood (Walker et al. 2001). The total system airflow was measured using a high-precision ($\pm 0.5\%$) flow nozzle between the return grille and the air handler fan. In addition, static pressures were measured in several locations throughout the system including the supply and return plenums. These flow measurements, together with the power law pressure drop models and the local loss coefficients developed in the component analysis were used to calculate the pressure drop in the supply branches of the system. The calculated pressure drops in the supply branches were then compared to the measured static pressure drops in the supply plenum. The static pressure was measured in the four upper corners of the supply plenum, and averaged for the sides corresponding to the supply branches. Figure 4 shows the location and the values of the

measured static pressure in the supply plenum. Our numbers therefore do not show the total external resistance that the fan operates at (which includes the furnace, cooling coil, return duct and filter). The results of the pressure drop calculation in the supply side of the installed system are summarized in Table 9. The calculations based on the individual component measurements performed for this study gave the closest results to the measured static pressure drop in the supply plenum. ACCA Manual D underpredicts the pressure drop in the flexible duct and the supply boots while it overpredicts the pressure drop in the splitter boxes, resulting in an overprediction of the pressure drop in one of the supply branches, and in a trade-off in the other, giving a pressure value as good as our calculations. ASHRAE Fundamentals 2001 underpredicts the pressure drop in both the flexible duct and the rest of the duct fittings, resulting in an underprediction of the static pressure in the supply plenum.

TABLE 9. Installed System Calculated and Measured Static Pressure in the Supply Plenum

Source of Data	Static Pressure Drop, inch water (Pa)			
	Branch A		Branch B	
	Value	Difference	Value	Difference
Measured* (Reference)	0.162 (40.3)	-	0.143 (35.6)	-
Component Analysis	0.168 (41.8)	4 %	0.122 (30.4)	-15 %
ACCA Manual D	0.191 (47.6)	18 %	0.122 (30.4)	-15 %
ASHRAE Fundamentals 2001	0.123 (30.6)	-24 %	0.085 (21.2)	-41 %

*The measured values reported are an average of 117 values of 5 seconds readings.

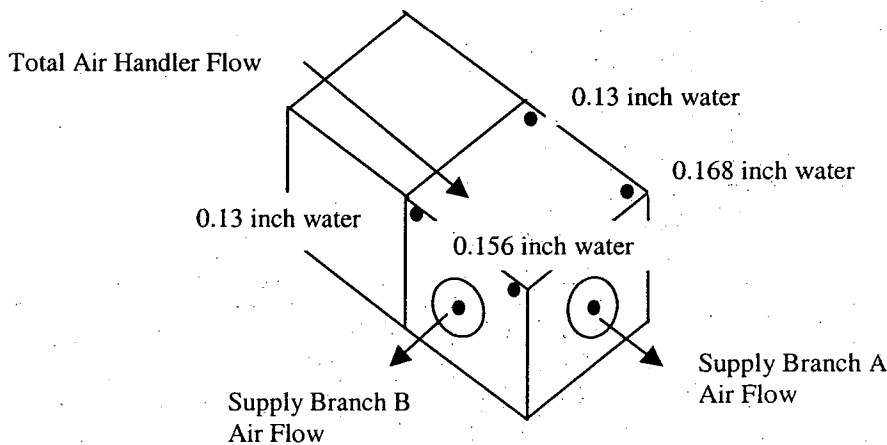


Figure 4. Location of the measured (upper corners) and calculated (at entry) static pressure values in the installed system.

Conclusions

This study provides detailed pressure drop data for compressed and bent flexible duct, splitter boxes, supply boots and an air intake hood that can be used to improve residential duct design calculations. Major contributions and conclusions of this study are:

- Compression effects of flexible ducts were analyzed and a new pressure drop correction factor was developed suitable for use in residential duct design calculations.

- The flexible duct elbows have much higher local loss coefficients (due to increased roughness) than those reported for sheet metal elbows.
- The supply boots results showed that both the installation and the diffusers have a major effect on the pressure losses in exit fittings.
- The local loss coefficient through a branch of the splitter box could vary substantially depending on geometry and flow ratios.
- The results from the tested air distribution system components were used in the complete duct system analysis and compared with available data from the literature. The comparison showed that our new data provide an improved estimate of the pressure drop for individual sections. Both the new data and existing ACCA procedures gave reasonable (less than 20% error) results for the total pressure drop. The ASHRAE calculation methods give large (20% to 40%) underpredictions.

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References

- Abushakra, B., Dickerhoff, D., Walker, I. and Sherman M. 2002. *Laboratory Study of Pressure Losses in Residential Air Distribution Systems*. Lawrence Berkeley National Laboratory Report LBNL-49293, Berkeley, CA (in press).
- ACCA. 1995. *Residential Duct Systems. Manual D*. Air Conditioning Contractors of America. Washington, DC.
- Altshul, A.D. and P.G. Kiselev. 1975. *Hydraulics and Aerodynamics*. Stroisdat Publishing House, Moscow, USSR.
- ARI 210/240. 1994. *Unitary Air-Conditioning and Air-Source Heat Pump Equipment (ANSI/ARI 210/240-94)*. Air-Conditioning and Refrigeration Institute.
- ASHRAE. 2001. *ASHRAE Handbook of Fundamentals*. American Society of Heating Refrigerating and Air-conditioning Engineers, Atlanta, Georgia.
- ASHRAE. 1995. *ASHRAE Standard 120P, Methods of Testing to Determine Flow Resistance of HVAC Air Ducts and Fittings, December 1995*. American Society of Heating Refrigerating and Air-conditioning Engineers, Atlanta, Georgia.
- IBACOS 1995. *Ventilation Ducts and Registers – Interim Milestone Report*. IBACOS, Pittsburgh, PA.
- Kokayko, M., Holton, J., Beggs, T., Walthour, S., and Dickson, B. 1996. *Residential Ductwork and Plenum Box Bench Tests*. IBACOS – Burt Hill Project 95006.13. Pittsburgh, PA.
- Proctor, J., and Parker, D. 2000. *Hidden Power Drains: Residential Heating and Cooling Fan Power Demand*. Proceedings of the 2000 ACEEE summer Study on Energy Efficiency in Buildings.

Tsal, R.J. 1989. Altshul-Tsal friction factor equation. *Heating, Piping and Air Conditioning*.
Walker, I.S., Wray, C.P., Dickerhoff, D.J., and Sherman, M.H. 2001. *Evaluation of Flow Hood
Measurements for Residential Register Flows*. LBNL 47382.

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