RATIONALE FOR MEASURING DUCT LEAKAGE FLOWS IN LARGE COMMERCIAL BUILDINGS

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ABSTRACT

Industry-wide methods of assessing duct leakage are based on duct pressurization tests, and focus on "high pressure" ducts. Even though "low pressure" ducts can be a large fraction of the system and tend to be leaky, few guidelines or construction specifications require testing these ducts. We report here on the measured leakage flows from ten large commercial duct systems at operating conditions: three had low leakage (less than 5% of duct inlet flow), and seven had substantial leakage (9 to 26%). By comparing these flows with leakage flows estimated using the industry method, we show that the latter method by itself is not a reliable indicator of whole-system leakage flow, and that leakage flows need to be measured.

KEYWORDS

Ducts, leakage, commercial, commissioning, measurements, diagnostics.

INTRODUCTION

Typically in North American large commercial buildings (floor area more than 1,000 m^2), central HVAC systems continuously supply heated or cooled air to conditioned spaces through a complex network of ducts. Large fan pressure rises are needed to move the supply air through the typically long duct runs, and the associated fan power is a substantial fraction (35-50%) of HVAC energy use. Fan energy can be reduced by using tight ducts that deliver conditioned air to where it is needed.

Although little is known about the duct system characteristics of existing buildings, three characteristics are notable. One is that the thousands of field-assembled joints between duct sections and duct-mounted accessories (e.g., VAV boxes) create numerous opportunities for leakage. The size and distribution of the leaks depends on the duct construction materials, and on the installation workmanship. Leakage testing of representative duct sections is necessary to verify that the installed system meets design specifications.

For a hole in a duct to be a problem, there must also be a pressure difference across it to drive the leakage airflow. Therefore, a second important characteristic is the pressure distribution in the duct system. Some duct sections operate at high static pressures (e.g., 100 to 2,500 Pa), but other sections, such as those downstream of VAV boxes, operate at much lower pressures (e.g., 10 to 100 Pa). In some systems, as much as 50 to 75% of the ducts may operate at the lower pressures (Fisk et al. 1999). Because of the spatial distribution of leaks and sometimes temporal variations in pressure, it is practically impossible to know the pressure difference across each leak. Although this lack of information means that leakage flows cannot be estimated with any quantifiable certainty, a common industry practice for estimating leakage flows is to assume that an average duct static pressure applies to every leak.

A third important characteristic is the location of the ducts relative to conditioned space. Leakage from a supply duct directly into a conditioned space is of little importance, except perhaps in terms of uniformity of air delivery, noise, and draft potential. In North American large commercial buildings, duct systems tend to be located inside ceiling return plenums, which are not conditioned space. In this case, supply air leakage can short-circuit the air distribution system, and the supply fan airflow must increase to compensate for the thermal energy lost through leakage.

Because the relationship between supply fan power and airflow is somewhere between a quadratic and cubic function, the increase in airflow to compensate for duct leakage means that fan power consumption increases significantly, with a large fraction used just to move the leaking air. Recent field measurements (Diamond et al. 2003) indicate that supply air leakage can increase fan power requirements considerably: a leaky system (10% leakage upstream of VAV boxes, and 10% downstream at operating conditions) uses 25 to 35% more fan power than a tight system (2.5% leakage upstream and 2.5% downstream at operating conditions).

The objective of this paper is to discuss the merits of duct leakage metrics and test methods that are used today by the building industry, and to present measured data that demonstrate the need for measuring duct leakage flows.

COMMON LEAKAGE METRICS

The building industry uses numerous metrics to describe duct leakage. A common metric is leakage rate (ASHRAE 2005), which is the leakage flow that would occur per unit of duct surface area if all the leaks were exposed to the same reference pressure. Leakage class is a related metric and is simply the leakage rate divided by the reference pressure to the 0.65 power. Standards and design specifications describe a wide range of reference pressures, and the reference is not necessarily the same as the average operating pressure in the system. ASHRAE suggests that the average leakage rate for unsealed (leaky) metal ducts at a reference pressure of 250 Pa is 2.5 $L/(s\cdot m^2)$; recommended leakage rates for tight ducts are 5 to 10 times smaller. Unfortunately, none of these estimates account for leaks at connections to grilles and diffusers, access doors, or duct-mounted equipment such as VAV boxes.

Another common metric in design specifications is leakage flow fraction, which is the leakage flow divided by a reference airflow. For an entire duct system or for “high pressure” ducts upstream of VAV boxes, the appropriate reference is the supply fan airflow. For “low pressure” ducts downstream of VAV boxes, the appropriate reference is the flow entering the box. For average unsealed leaky ducts, SMACNA (1985) suggests that leakage fractions of 6 to 77% can occur, depending on the system airflow and duct static pressure. To use this metric, one must know or estimate both the leakage flow and the reference flow. The following section describes the tests that industry currently uses to estimate these parameters.

DUCT LEAKAGE TEST METHODS

Instead of measuring total leakage flows at operating conditions, test and balance companies typically estimate the leakage rate using an industry-wide method (SMACNA 1985):

pressurize a sealed duct section using an auxiliary fan and, using a flow meter integrated with the injection apparatus, measure the airflow required to maintain a reference pressure difference (assumed to be the same across every leak).

Unfortunately, because it is difficult to temporarily seal and test the often numerous "low pressure" ducts downstream of VAV boxes with this method, few guidelines or construction specifications require testing these ducts. Thus, testing focuses on the "high pressure" ducts (anecdotal evidence suggests that such tests sometimes are carried out even before branch ducts are attached). Not testing "low pressure" ducts downstream of VAV boxes is a problem, because these "branch" ducts can be a large fraction of the system and, as shown later in Figure 1, these ducts tend to be much leakier than upstream "main" ducts. Testing only the "high pressure" ducts does not guarantee a tight system if the "low pressure" ducts are leaky. Both parts of the duct system need to be tested.

Even if the pressurization test was used to assess the leakage of the "low pressure" ducts, the variability of operating pressures in these ducts makes it difficult to define an appropriate reference pressure. To overcome this difficulty, whole-system leakage airflows at operating conditions can be determined by measuring the airflow out of each supply grille, and by measuring the supply fan airflow; the difference between the sum of the grille airflows and the supply fan airflow is the leakage. If desired, the leakage of individual duct sections can also be tested by measuring the inlet flow to the section. It is necessary to keep the supply fan airflow and all VAV box damper positions (when applicable) constant during the test.

In practice, conventional flow measurement methods generally are not accurate enough to assess duct leakage flows. For example, pitot-static tube traverses to measure duct and fan airflows have an accuracy of only about 5 to 10%. Our recent laboratory tests of commercially-available flow capture hoods indicate that many hoods have substantial bias and precision errors (10 to 20%), although some hoods are quite accurate (2 to 5%).

Less-conventional methods can accurately measure leakage flows. These tests involve constant-injection tracer gas techniques (with expensive gases and analyzers and with careful attention to mixing) to measure supply fan airflows (accuracy of 3 to 4%), and powered flow-hoods to measure supply grille airflows (accuracy of 1 to 2%). Powered hoods are insensitive to the flow non-uniformities that lead to errors with conventional hoods. However, powered hoods are slow and cumbersome to use, especially in occupied buildings (e.g., it took five people 12 hours to measure airflows from about 100 supply grilles in one building). To make leakage flow measurements more practical, inexpensive, rapid, and accurate tracer-gas based systems with enhanced mixing need to be made commercially available.

DUCT PRESSURIZATION TEST RESULTS

Figure 1 shows the few duct pressurization test data that researchers have collected over the past several years in nine U.S. large commercial buildings (Xu et al. 1999, 2000; Fisk et al. 1999; Diamond et al. 2003). These data include VAV, CAV (constant-air-volume), and dual-duct systems, and both "high-pressure" ("main") and "low-pressure" ("branch") duct sections. For VAV systems, the data include fan-powered boxes ("VAV Fan") and cooling-only boxes. Most of the systems supply air through rectangular diffusers, but some use slot diffusers.

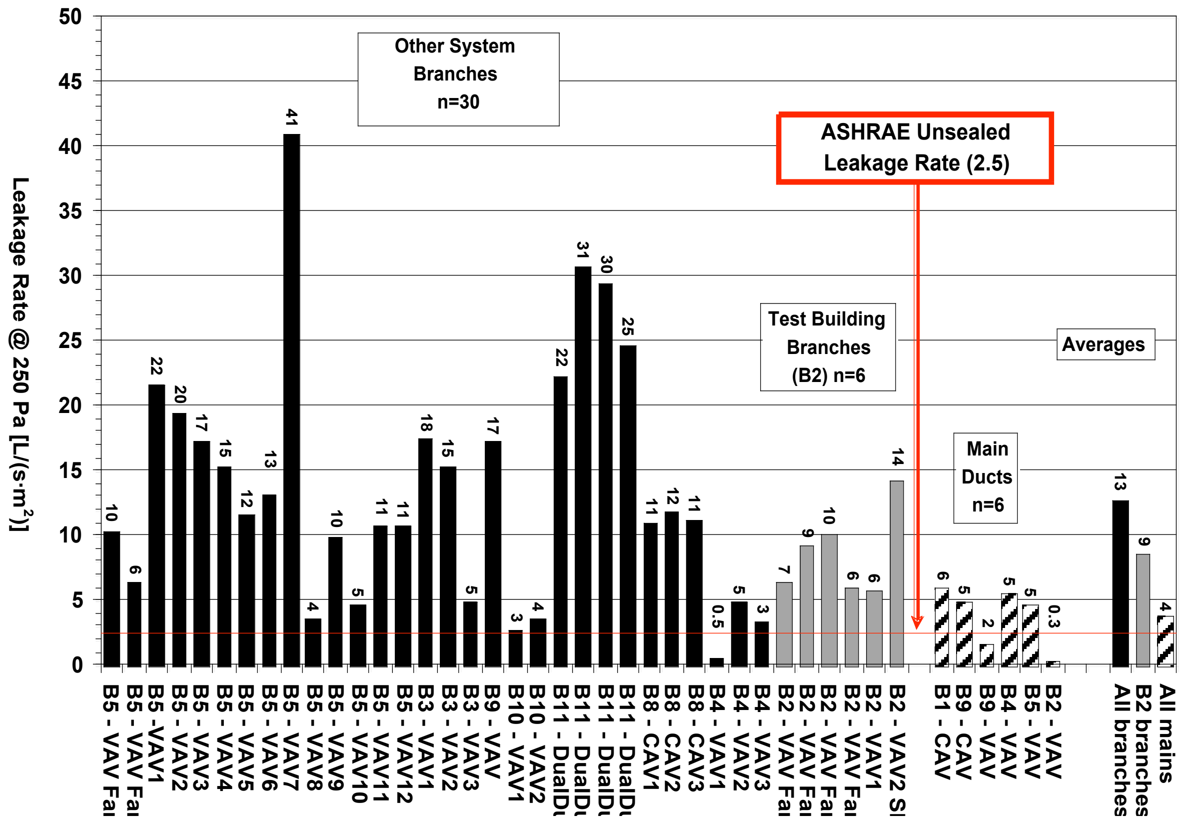

Figure 1: Duct Leakage Rates

Figure 1 suggests that there is a wide range of duct leakage in U.S. large commercial buildings. On average, branch ducts are about three times leakier than main ducts (perhaps in part because the branch ducts are not usually tested). Even many of the main ducts, which might have been tested during post-construction test and balance activities, are leakier than the average unsealed leakage rate suggested by ASHRAE.

Building 2 (B2) contains the system used by Diamond et al. (2003) to assess the fan power impacts of duct leakage. The intent of the study was to seal leaky ducts and to measure the resulting change in fan power. The pressurization test data in Figure 1 indicate that the branch ducts are leaky; however, as described in the next section, it turned out that the duct system was actually very tight in terms of leakage flows, and substantial duct leakage had to be added instead to carry out the study.

DUCT LEAKAGE AIRFLOW TEST RESULTS

Figure 2 shows measured leakage flow fractions for 10 systems in nine U.S. large commercial buildings. The data are for whole-systems, as well as duct branches. The reference flows that we measured at operating conditions are listed for each test. Where corresponding duct pressurization test data are available, we used these data to estimate the leakage fraction that the tested part of the duct system would experience at its average operating pressure. In other words, for the conditions at which the leakage flow measurements were made, we calculated the leakage fraction that would be implied by the standard industry pressurization test (if it were applied to the duct sections included in the measured leakage flow test). For whole-systems, we estimated leakage flows section by section using the average operating pressure associated with each section, and then divided the sum by the total inlet flow for the system.

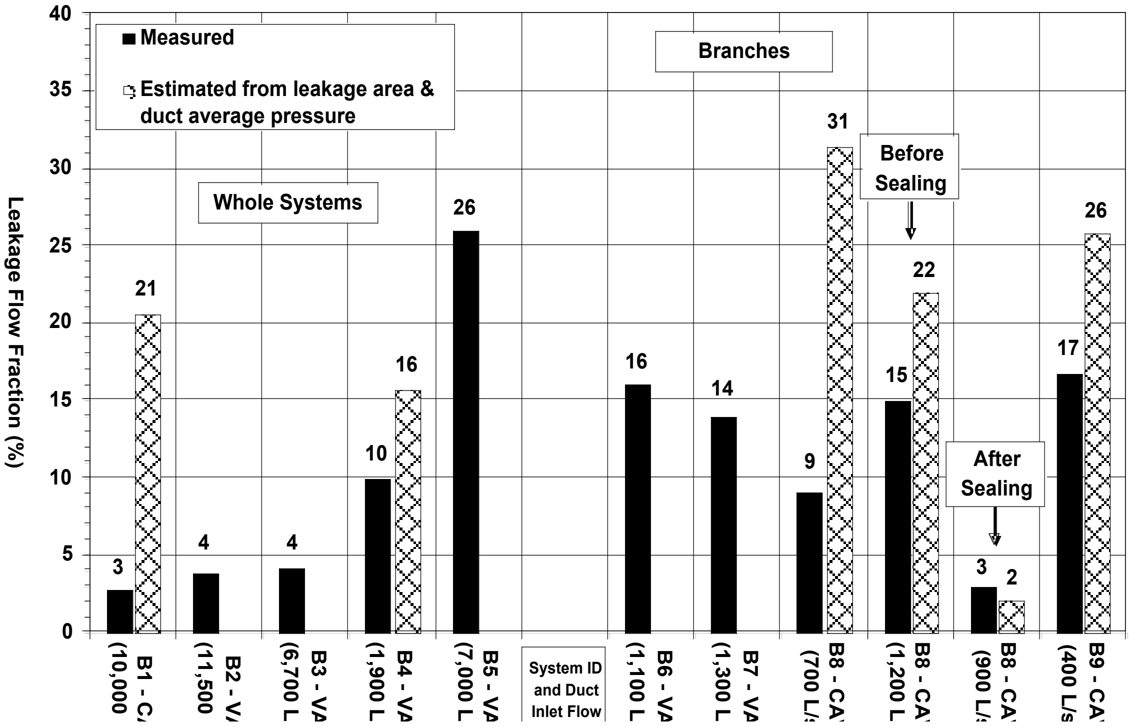

Figure 2: Duct Leakage Flow Fractions

The discrepancies between measured and estimated leakage flow fractions mean that the estimates are not a reliable indicator of actual leakage, and leakage flows need to be measured. In particular, the estimated fraction for Building 1 is seven times greater than the measured fraction. This estimate is not useful to show compliance with design specifications, and could lead to adversarial relations between designers, installers, and test and balance contractors. One can imagine the installer being told to do a better job, because the estimate indicates the ducts are leaky, when in fact the workmanship is good and the ducts are tight.

The principal reasons for discrepancies are that the pressurization tests unintentionally included gaps between diffusers and the ceiling grid, and the operating pressures at these gaps and at other leaks are lower than the average operating pressure. During the test, diffusers were sealed with a covering fastened to the adjacent ceiling grid, which means that the diffuser-grid gaps were inside the sealed system during the test. Consequently, the gaps appear to be duct leaks, even though they are not leaks during normal operation.

Figure 2 indicates that there may be a substantial number of leaky duct systems in the building stock: three systems had low leakage (less than 5% of duct inlet flow), and seven had substantial leakage (9 to 26%). There is also good news: some installers already can produce tight duct systems. Rather than requiring new construction and sealing techniques, it appears that installers of leaky systems only need training to use industry best practices. Measuring duct leakage flows would help demonstrate progress toward this goal.

As a retrofit to reduce leakage, the duct systems in Building 8 were sealed using aerosol-based sealants. Our tests on Branch 2 indicate that the sealing substantially reduced leakage. Note that the reduced inlet airflow after sealing is likely because the building operators adjusted the fan speed between tests, and is not caused by the sealing itself. The estimated leakage flow fraction agrees well with the measured fraction for the "sealed" case. Small estimated fractions are good indicators of a tight system; the converse is not true for large fractions that indicate a system is leaky.

SUMMARY

Duct leakage can considerably increase fan energy use in large commercial buildings. Industry-wide methods of assessing leakage are based on pressurization tests of “high pressure” ducts, and make broad assumptions regarding the interactions between leaks and duct static pressure. Even though “low pressure” ducts can be a large fraction of the system and tend to be leaky, few guidelines or construction specifications require testing these ducts. Both parts of a duct system need to be tested.

We have used complex techniques to measure leakage flow fractions for ten large commercial duct systems at operating conditions: three had low leakage (less than 5% of duct inlet flow), and seven had substantial leakage (9 to 26%). Comparisons of these fractions with fractions estimated using the industry method show that small estimated fractions are a good indicator that a system is tight; the converse is not true for large fractions that indicate a system is leaky. Leakage flows need to be measured to properly commission a duct system.

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