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Local leakage measurement and Cfd prediction of k-factors of leaks in residential HVAC ducts

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LOCAL LEAKAGE MEASUREMENT AND CFD PREDICTION OF *K*-FACTORS OF LEAKS IN RESIDENTIAL HVAC DUCTS

by

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ABSTRACT

Local Leakage Measurement and CFD Prediction of *k*-factors of Leaks in Residential HVAC Ducts

by

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The experimental work in this research focuses on a new technique, Duct pressurization Local Leakage (DPLT) technique, developed to locate leaks in residential HVAC ducts and to quantify their leak rates. The local leakage rate determined by this technique was compared with known leakage from artificial holes. This technique was also evaluated by comparing the measured total leakages with that determined by standard duct pressurization test and Delta Q. The tests were conducted at the Air Duct Leakage Laboratory (ADLL) which has two air distribution systems and a wide range of leakage rates. The technique produces relatively small scatter and bias. The proposed technique estimates the local leakage accurately. The smoke tests confirmed the leak locations visually.

A three-dimensional computational fluid dynamics (CFD) model was used to simulate fluid flow in a duct with six different leak geometries. The k-ε turbulence model for high Reynolds numbers flows was used for that purpose. The Reynolds numbers were varied to simulate a variety of flow conditions. The computer code was used to produce

pressure drop data around the holes necessary to compute the pressure loss coefficients, as well as to produce flow field and static pressure plots that offer insight into the physics of the flow field. The flow coefficient and pressure exponent were found for different leak geometry by curve fitting the pressure and leak flow data derived from CFD simulations. Also, a correction factor was found out for an existing ventilation duct leakage formula that calculates the leakage flow. The correction factor reduced the mean absolute error from 49% to 6%.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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Finally, I would like to thank my parents, Subhash Rao and Ratnamala Gundavelli, my siblings and friends, for their support throughout my entire education and especially to my parents, for allowing me the opportunity to pursue higher education. They have provided me with an ideal support system and I am grateful for that.

CHAPTER 1

LITERATURE REVIEW

Heating ventilation and cooling energy accounted for 356000 GWh, 31 percent of the total electricity consumed by U.S. households in 2001 (EIA 2001). Central air-conditioning alone accounts for almost half of the HVAC total. Field studies (Jump et al. 1996; Cummings et al. 1990; Downey and Proctor 1994; Modera and Wilcox 1995) indicate that in existing residential buildings 30-40% of the total air handler flow is lost in the form of duct leakage to inside and outside. This indicates that roughly 54000 GWh of energy is being wasted in residential buildings. The significance of duct leakage testing has been reemphasized in the last two decades due to energy, health and comfort concerns (Cummings et al. 1990; Andrews et al. 1991; Olson et al. 1993; Palmiter et al. 1995; Jump et al. 1996; Siegel et al. 1996; Davis et al. 1997; Walker et al. 1998a; Siegel et al. 2003; and Francisco et al. 2002a, 2002b, 2003a, 2003b).

Loss of conditioned air to unconditioned spaces is a direct source of energy loss and leads to higher energy bills. The average retail price of electricity for residential consumers increased by 0.79 cents per kWh between October 2005 and 2006 (EERE 2007). There are more that 101 million residential households in the United States today and residential buildings therefore represent the single largest source of potential energy savings. Experimental studies indicate that the cooling capacity and coefficient of performance of the air conditioning system decreases with increase in return air leakage, (Dennis et al 2002). Also leakage on the return side causes unfiltered air to enter the duct system and can create indoor air quality problems. Deposition of this dust on the coils reduces their performance. Large leaks or disconnected supply ducts cause certain areas of the house to be uncomfortable. These energy and comfort issues are some of the reasons why homeowners and researchers are now looking for ways and means to reduce duct leakage.

CHAPTER 2

INTRODUCTION AND BACKGROUND

2.1 Significance of Research

Industry wide duct leakage measurement techniques have been able to find only the total leakage in duct systems. Tests like the duct pressurization techniques (ANSI/ ASHRAE standard 152-2004) and blower door test assume that the entire duct system is at a uniform pressure to estimate the total leakage in the duct system. Pressure however, is a very important parameter and varies drastically along the length of the duct at operating conditions. The leakage in sections of the duct that is at a higher pressure is under represented and in the rest of the duct is overestimated, when one assumes a single averaged pressure along the entire duct length. Delta Q techniques tries to estimate the leakage at operating conditions by using fitted pressures (Walker et al 2002). None of the tests however, yield any information about the location of the leak. These details are of primary importance to the home owner when one is trying to mitigate the problem of duct leakage. Tracer gas tests can identify leak locations to some extent. Also, aeroseal technique tries to seal leaks irrespective of their locations (Modera 2005). These techniques are however expensive and time-consuming.

Computational Fluid dynamics packages are now being widely used in industry and research alike to simulate phenomena like fluid flow, heat transfer and diffusion.

They may be used to simulate physical processes where physical measurements are not possible or are very difficult or costly. Industry wide experimental methods are used to measure leakage from ducts. However, very little insight has been offered into the actual physics of the flow inside residential HVAC ducts.

The objectives of this research are

1. To find localized leak locations in duct systems and to quantify the leakage rates using experimental techniques
2. To perform numerical simulations in an effort to provide flow parameters; this can help in characterizing leaks and to study the relationship between leak geometry and leakage rate

These objectives were achieved by incorporating the following steps

1. Established an experimental facility Air Duct Leakage Laboratory (ADLL)
2. Established a baseline for validation of experimental technique
3. Developed an experimental method for locating leaks and quantifying their leakage rates
4. Used CFD modeling to simulate different leak shapes in ducts

The key contributions of this research are

- Identification of leak locations and precise quantitative estimation of local and total leakage rates using a new experimental technique.
- Detailed insight to understand the physics of flow in different leak geometries

Background

Air Conditioning Systems

The aim of air conditioning systems is to provide a regulated indoor environment that is comfortable to the occupants despite changes in external weather conditions or heat loads. This is achieved by controlling factors like temperature and humidity. The air conditioning system consists of three main parts: air handling unit (AHU), supply ducts and return ducts. Typical parts of a split system used for residential air- conditioning are condenser, compressor and the evaporator. AHUs are selected based on the cooling load of the building and weather conditions. Ducts are sized using the static regain method or the equal friction method (Mc Quiston 2000). Ducts are generally placed in attics or crawl spaces. As the duct has to run through a complex maze of trusses, flexible duct is considered to be more convenient than the other types. These are made from flexible plastic with wire coil reinforcement (Figure 2.1). Insulated flex duct has a layer of fiberglass insulation over the duct and a thin metalized or polythene jacket that protects the insulation. Supply ducts are connected between the AHU and the supply air outlets. Metal fittings allow for portion of the flow in the main duct to be diverted into branch ducts.

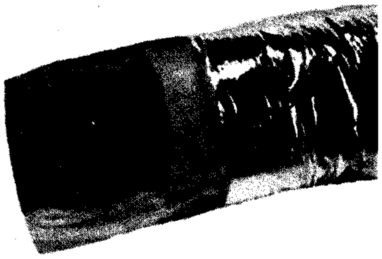

Figure 2.1 Flex Duct (www.llbuildingproducts.com)

Without any leaks in the duct, the air distribution system is a pressure-balanced loop, with the same amount of air entering and leaving the conditioned space. When the air handler is turned on, the fan housed in the air handling unit forces air into the supply ducts (Figure 2.2). The ducts deliver this air to rooms in the house through air outlets such as registers. The warm air in the building envelope, exits through return grilles(when the building is being cooled), where negative pressure from the fan's intake pulls the air through return ducts back to the air handler via a filter that removes dust.

2.2.2 Losses in HVAC Systems

Air infiltration/exfiltration: Air infiltration/exfiltration occurs through gaps and cracks in the building envelope, around windows and doors, and through penetrations between conditioned and unconditioned space. This can be a major source of energy loss. Air infiltration can draw in humidity during the cooling season, and create uncomfortable drafts during the heating season.

Inadequate Insulation: Substantial heat can be lost through windows and doors as they are very poor insulators. The amount of heat lost in this form depends on the location and size of windows and doors..

Ductwork: Research indicates that air conditioning ducts are a major cause for energy wastage in residential buildings (Jump et al. 1996, Siegel et al. 1998, Davis et al. 1998, Walker et al. 1998, Siegel et al. 2003 and Francisco et al. 2002a, 2002b, 2003a, 2003b). Ducts placed in the unconditioned space are exposed to extreme temperatures. Energy is lost constantly from the duct to the surroundings due to heat transfer and duct leakage causes a direct loss of thermal energy from the forced air distribution system. Some of the common duct problems as depicted pictorially in Figure 2.2.

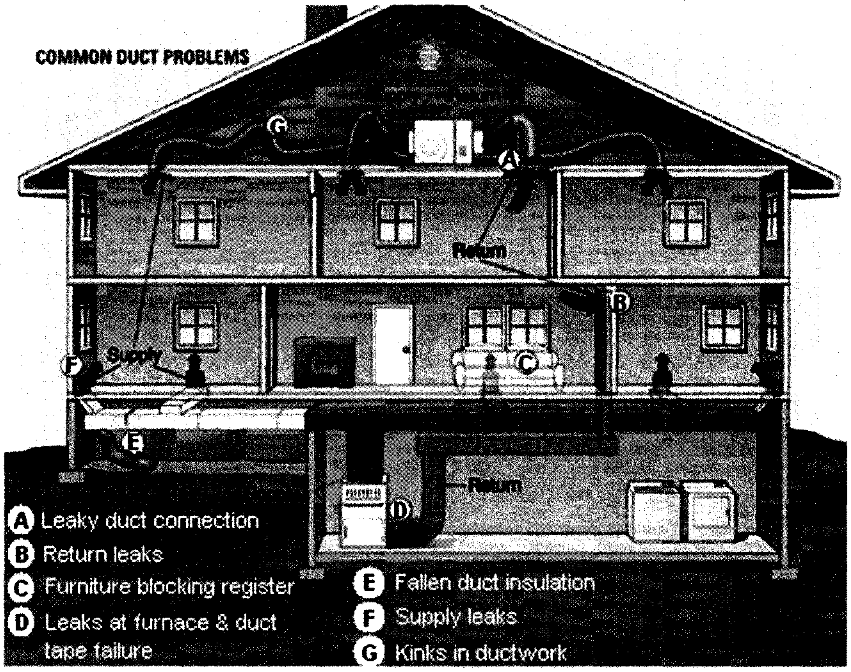

Figure 2.2. Common Duct Problems (Source: http://www.renovation-headquarters.com/heating-ductsealing.htm)

2.2.3 Causes of Duct Leakage

Numerous field-assembled joints between flexible duct sections and duct-mounted accessories create opportunities for leakage. Each of these joints requires a sealant to keep them connected. A range of sealants like duct tape, butyl tape, foil tape, mastic etc are available on the market. The quality of workmanship affects the durability of the seal (Figure 2.3). Studies indicate that duct tape tends to deteriorate in its performance when used for three dimensional joints. It is also sensitive to dust and greasy surfaces (Bass 2002).

2.2.4 Effects of Duct Leakage

Energy loss: In homes where the ducts are placed inside the unconditioned space, any leakage would cause loss of conditioned air and thus cause energy loss.

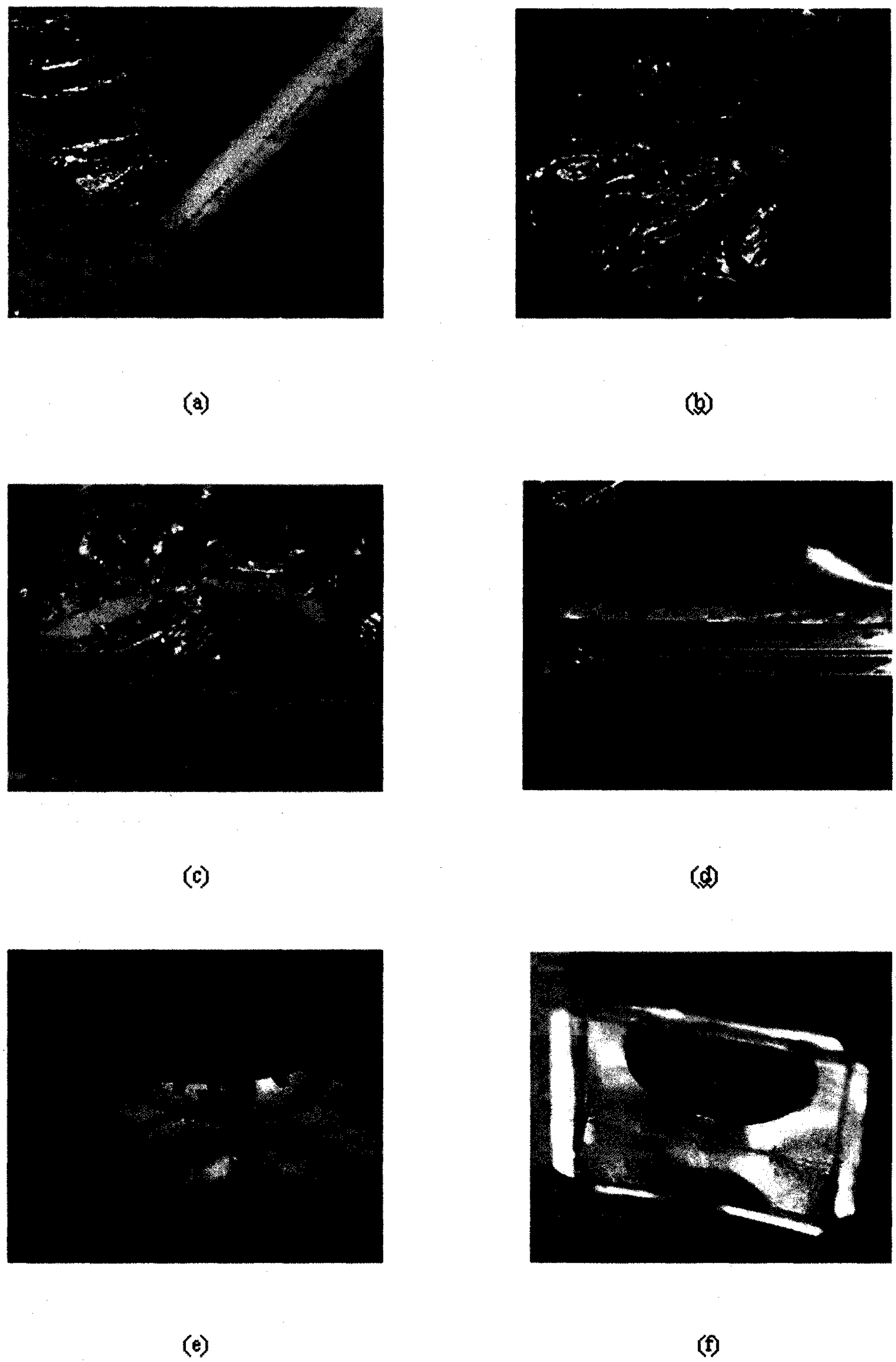

Figure 2.3 Common Causes for Duct Leakage: (a) Direct Contact with Metal Fixtures (b) Metal Strap Used as a Support Tearing into the Insulation (c) Loose Terminal Connection (d) Warped Boot and Loose Terminal Connection (e) Incomplete Crimp joint (f) Inadequately Fastened Boot

Occupant comfort: In houses where most of the leakage is to inside, effects may not appear as loss of thermal energy. However, such leaks tend to reduce the amount of air that the recipient room or zone that it is designed to receive. Consequently, some of the rooms in the house may appear to be at a different temperature than the rest. The difference in these temperatures is again dependent on the amount of leakage.

Health Concerns: Return ducts that are placed outside the conditioned space tend to draw air that may contain dust or other air borne particles though the leaks. This air does not bypass through the filter and so the dust is carried to the air handler and to the indoors.

2.2.5 Leakage Measurement Techniques

Leakage testing of representative duct sections is necessary to verify that the installed system meets design specifications. Almost random distribution of leaks and variation of pressure in ducts makes it difficult to know the pressure difference across each leak and therefore the leakage through the hole. Industry wide methods that are currently available measure the overall leakage in the duct system or leakage from the envelope. Some of these methods are as follows.

2.2.5.1. Duct Pressurization Test

This test is part of the ANSI/ ASHRAE standard 152-2004. In this test a duct blaster (Figure 2.4) is connected at the air handler or the supply register. The registers are sealed off. The duct blaster is then run to maintain a test pressure like 25 Pa in the duct system. The flow through the duct leaks will then be replaced by the flow from the duct blaster. Total leakage is thus obtained at the test pressure. To increase the accuracy of the test a more comprehensive test called the multipoint test may be conducted at several values of test pressures. The pressure and leakage values are then mapped. The leakage at half the plenum pressure is used as a representative is assumed to be the leakage from the duct system. The main disadvantage with this method is of course the assumption that the entire duct system is assumed to be at half the plenum pressure.

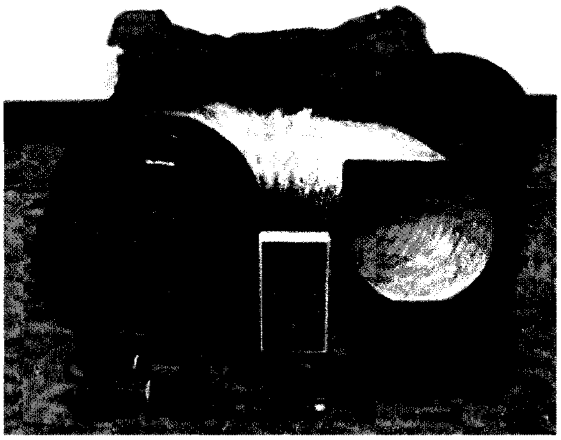

Figure 2.4 Duct Blaster (Source: www.energyconservatory.com)

2.2.5.2. Blower Door Test

The blower door test places a home under a known pressure and then measures how much airflow is required to maintain the pressure difference between indoors and outdoors. The tighter the house, the less air the blower door (Figure 2.5) must move to maintain a given pressure.

2.2.5.3. Nulling Test

Nulling test uses a blower door to match the pressure in the house with the system fan on to a target value measured with the system fan off. With the duct system in its as-found condition, the flow rate through the fan is then equal to the unbalanced duct leakage. By blocking off the return portion of the system and using a duct blaster to feed the supply side of the duct system, the same technique can be used to measure the supply leakage separately. The return leakage is then calculated as the difference between the supply leakage and the unbalanced leakage.

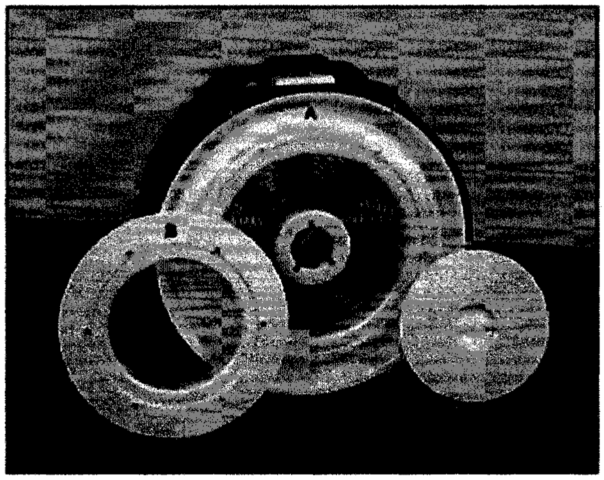

Figure 2.5.Blower Door (Source: www.energyconservatory.com)

2.2.5.4. Delta Q Test

Delta Q combines a model of the house and duct system with the results of house pressurization tests with the air handler on and off to determine the duct leakage air flows to outside conditioned space at operating conditions. Pressure across the duct and the encompassing leaks is varied by pressurizing and depressurizing the house over a range of test pressures using a blower door. The delta Q model for duct leakage is given by the following equation (Walker et al., 2002):

$$\Delta Q(\Delta P) = Q_s\left[\left(1+\frac{\Delta P}{\Delta P_s}\right)^{n_s} - \left(\frac{\Delta P}{\Delta P_s}\right)^{n_s}\right] - Q_r\left[\left(1-\frac{\Delta P}{\Delta P_r}\right)^{n_r} + \left(\frac{\Delta P}{\Delta P_r}\right)^{n_r}\right] \tag{2.1}$$

where

ΔP_s is the characteristic pressure difference between supply and house

ΔP_r is the characteristic pressure difference between house and return

Q_s is the supply leakage flow

Q_r is the return leakage flow

The unknowns are determined using statistical algorithms to determine the values that best fit the data. An important feature of the Delta Q is its direct determination of air leakage flows and identification of supply and return leakage flows.

2.3. Air Duct Leakage Laboratory

The main objective of the research project was to address the issue of duct leaks in residential air distribution systems. The need was therefore felt to test the proposed techniques in systems that are representative of the duct systems of typical tract type homes in Las Vegas area. Air Duct Leakage Laboratory (ADLL) was set up accordingly (Figure 2.6). The available area of 30'X10" square footage was originally bounded by walls and equipped with basic electricity. With the help of a local building contractor dry wall partitions were installed dividing the area into three rooms of approximately same area. Two soffits were built along the east and the west wall of the building. The soffits are vented to the outside to simulate attic ventilation. One of the lateral surfaces of the soffits has been sided with drywall and the other with transparent plexiglass (See Figure 2.7). The soffits space also envelopes wooden trusses placed between equi-spaced studs.

2.3.1. Energy Plus Simulation

Energy Plus is a new generation of building energy simulation software developed by the U.S. Department of Energy. The first version 1.0.0 was released in April 2001 and the latest version 1.2.3 was released in October, 2005.

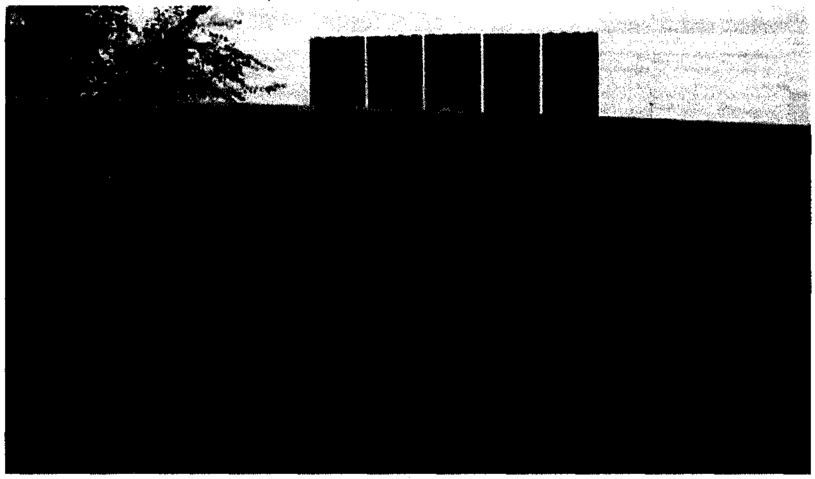

Figure 2.6 Air Duct Leakage Laboratory

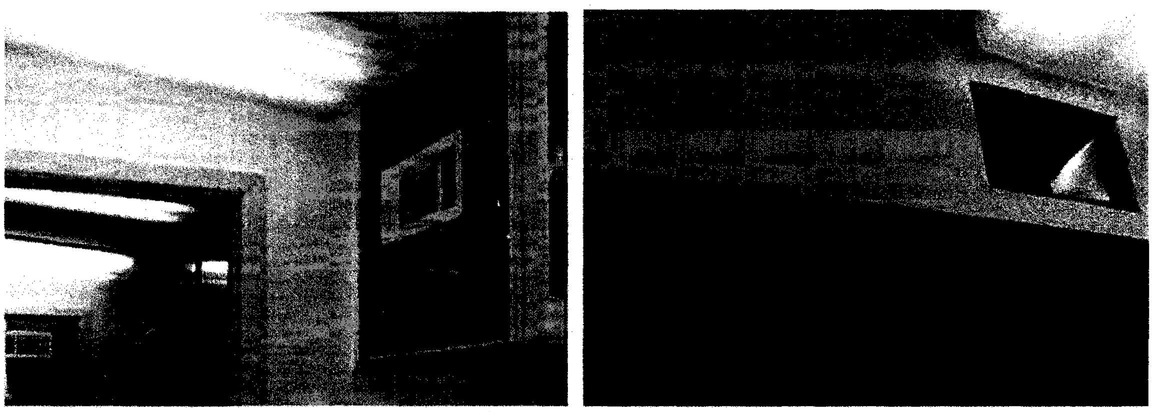

Figure 2.7. Soffits for Air Distribution Systems I and II respectively

Energy Plus is built on popular features and capabilities of both BLAST and DOE-2 but also includes several innovative simulation capabilities such as flexible sub-hourly time steps, modular HVAC systems, multi-zone airflow, thermal comfort, and photovoltaic systems. Energy Plus is expected to be a valuable tool to simulate building energy use and study control strategies of building mechanical systems to reduce both building energy consumption and operating costs. In addition, the expanding capability also includes a detailed air distribution system (ADS) models that can be used to predict the detailed behavior of forced-air distribution systems coupled with buildings. The present ADS model in Energy Plus is one of the detailed models and is used to simulate thermal conduction and air leakage losses for air distribution systems in residential or light commercial buildings.

At the design stage, the Energy Plus model was developed to simulate the thermal response of the building in design condition, which provides the peak cooling and heating load for the needs of sizing the HVAC system including heat pump unit and the duct system.

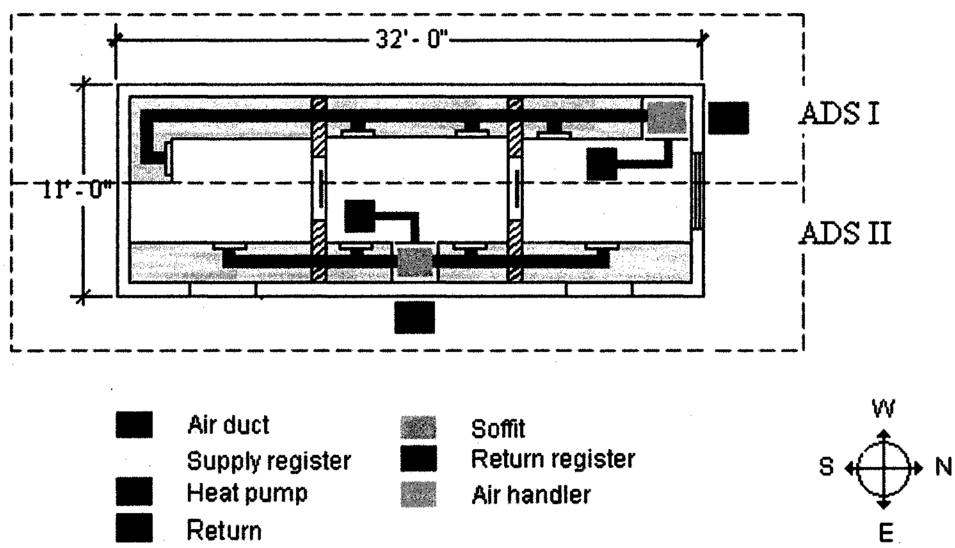

Figure 2.8 Floor Plan of the Test Facility

calculated from Energy Plus simulations. According to the peak load at the design condition obtained from the simulation result, two heat pump units were selected as the cooling/heating equipment for the laboratory building. Each unit had approximately 1.5 ton cooling capacity. Two HVAC units, one in the northwest corner and the other unit on the east side were installed (Figure 2.8). The specifications of the air handler and the heat pump are listed in Table 2.1.

Table 2.1. Specifications: Air handler and heat pump

Air handler Specifications		Heat pump Specifications	
Size	1.5 ton single phase unit	Compressor type	Scroll
CFM (Nominal)	800	Refrigerant	Puron
Energy Efficiency	13 SEER / 11.5 EER/7.9-8.5 HSPF	Air quantity	2614 cfm

2.3.2 Air Distribution Systems

The air flow capacity of the system was 450 CFM/ton. The ducts were sized using the equal friction method (Mc Quiston 2000). The system itself is a relatively simple distribution system, but the ducts were installed in the typical residential fashion, in order to allow for a comprehensive evaluation of duct leakage. Two independent HVAC units were installed with different duct configurations, indicated by Air Distribution System I (ADS I) and Air Distribution System II (ADS II), respectively (See Figure 2.8). The first air handler (ADS I) is in the northwest corner of the building with the flex duct running along the west wall. The duct branches off in an asymmetrical fashion to four different registers from three regular sheet metal Y connections. For ease of identification numbers are designated to the registers and the Y connections. The second air handler (ADS II) is placed in the middle room. The duct configuration is symmetrical in this case. The flex duct runs on either sides of the supply plenum along the east wall. Air is supplied through four registers with just one sheet metal Y connection. The flex duct runs through a series of flat trusses in the framed soffits (Figure 2.9). The heat pumps are outdoor-mounted, air-cooled, split systems (Figure 2.10). The ducts in ADS II are housed in the dropped soffits completely, whereas in ADS I they are partially open to the inside. The former demonstrates leakage to outside and the latter, leakage to inside. The supply plenum is placed right on the air handler. The return system is open to the inside. It has just one return grille that is ducted to the return plenum placed under the air handler.

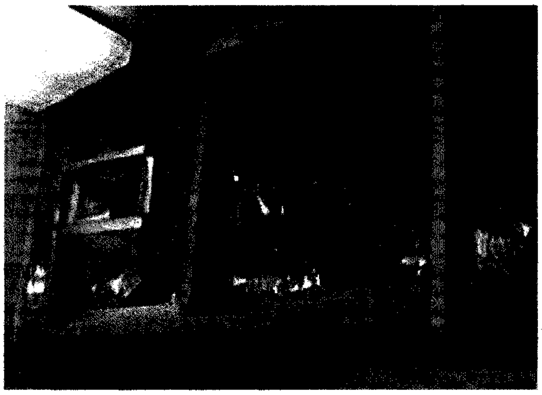

Figure 2.9 Truss Structure in Soffits

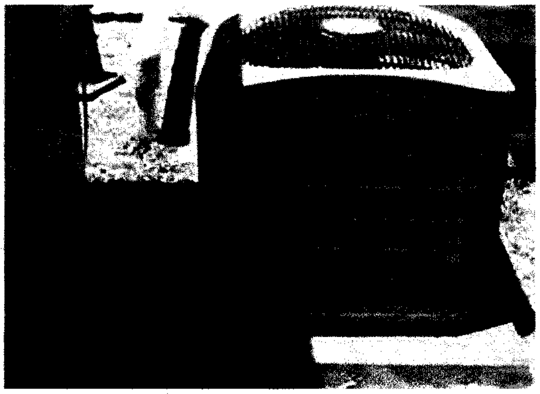

Figure 2.10. Heat Pump

2.3.3 Versatility: Air Duct Leakage Laboratory

One aspect that was taken care of during setting up the lab was versatility. A number of standard techniques and proposed techniques needed to be tested in the facility. With two air handlers one would just be confined to two air distribution systems. However, when working with new techniques one very important issue is repeatability. And to check for repeatability, any technique should be tested a number of times and on a number of systems. Air Duct Leakage Laboratory therefore is equipped with versatile features. For example, the total leakage for the ducts can be varied between 5 and 25% by adding artificial leaks in different locations. The leakage from these holes could easily be calculated by conducting the fan pressurization test before and after creating the holes.

Ducts in ADS II are originally housed completely in the soffits. Whereas for the ADS I, the soffits envelopes only a part of the ducts. This could be later modified so that the entire duct system could be enclosed in an envelope that is connected to the attic. Similarly, the return ducts were originally designed to be open to inside and with little effort could be held in an envelope that is connected to the outside. This in a way provided additional variation so that leakage to inside could be transformed to leakage to outside and vice versa.

CHAPTER 3

EXPERIMENTAL DETERMINATION OF LEAK LOCATIONS AND MAGNITUDES

The flow pressure relationship is an important characteristic in duct flows. Several research efforts have been conducted experimentally regarding duct leakage estimation to analyze the impact on the overall system. Most of the researchers however focused on total leakage measurements from the duct system by assuming a single static pressure along the length of the duct. In other words, the pressure-flow relationship was being expressed as a single equation with two variables: pressure and flow. One would plug in the value of the average static pressure to find the overall leakage. However, the pressure along length of the duct varies significantly. The basic idea in this work is to virtually break up the duct into smaller segments and obtain the leak rates in each of them individually. This would facilitate identification of the leak locations and to quantify the leak rate from each of these locations.

The technique proposed for local leakage estimation relies on isolating the duct system sequentially and finding the leakage in each section of the duct. This technique will be referred to as the Duct Pressurization Local leakage Technique (DPLT). Before applying the test, it is advisable to conduct a simple duct pressurization test to find the total leakage of the duct as a percentage of the fan flow. If this number is above 5%, it may be necessary to repair ducts or find the leak locations. Apart from characterizing the existing ducts at the Air Duct Leakage Laboratory, some artificial leaks were added. The artificial leaks thus created not only provided more leakage configurations but also were used to establish a baseline to validate both the proposed techniques. The test procedure for the proposed technique and scope and details about the baseline tests will be dealt with in this chapter.

3.1. Duct Pressurization Local leakage Technique (DPLT)

As the name suggests, DPLT is based on the existing duct pressurization technique. Apart from the instrumentation required for the duct pressurization test, zone bags will be needed. The description of a zone bag, the parametric studies done on zone bags and the DPLT test procedure will be discussed next.

3.1.1. Zone Bags

Zone bags are generally used in duct cleaning to block sections of ducting to make big jobs more manageable during duct cleaning. Commercially available zone bags are made up of a thick inner bladder covered with a layer of puncture resistant vinyl cloth and the open end of the rubber bladder is connected to a PVC hose with a ball valve on its end through which the bag can be pressurized (Figure 3.1). The zone bags are introduced into a section of the duct and then inflated using compressed air. In a completely inflated state the zone bag fills into the ridges of the helical groves of the flex duct to give a larger area of contact to provide air tightness (Figure 3.2). Isolation of duct sections will allow gradual sequential identification of leaks.

Figure 3.1 18" Zone Bag

Figure 3.2 Fully Inflated Zone Bag Inside the Duct

3.1.2. Parametric Studies on Zone Bags

The primary focus of these tests was to investigate the effectiveness of zone bags to block the air flow in flexible ducts. Parametric studies were performed to determine the right amount of pressure that can be introduced in the zone bags. The tests were conducted on a straight duct as well as a tee section with diameters such as 8", 10", 12", and 14". One leg was connected to the calibrated fan and the remaining legs were blocked using sheet metal duct caps. Multipoint pressure testing was done on this set up recording the duct pressure and the calibrated fan flow. This served as an estimate of the inherent leaks in the system and a baseline to test the effectiveness of zone bags. The duct caps were then replaced with zone bags and the test repeated while varying the pressure in the zone bags. Figure 3.3 and Figure 3.4 show the effectiveness of the zone bags in straight duct and tee section ducts respectively and for different pressures inside the duct and zone bag. It is indicated that the performance of the zone bags is very close to that of the duct caps when the pressure inside the zone bag is higher than 0.28 PSI. Increasing the pressure in the zone bag might improve the seal between the zone bag and the duct. Nevertheless, there is a clear possibility that the zone bag will burst. It is evident from Figures 3.3 and 3.4 that if the zone bags are pressurized to the right extent, its performance can match that of a physical restriction, in this case sheet metal duct caps. Based on such observations, the operational range of pressures for the zone bags was identified (Table 3.1). The leakage from the system when the duct caps are used may be attributed either to the leaks in the system or due to improper sealing between the duct and zone bag. Even if the 2 cfm leakage in the straight duct is attributed entirely to the latter reason, the overall effect is that the leakage may be overestimated by 1% of total air handler flow.

Another aspect that needs to be discussed here is the sudden decrease in leakage at high duct pressures. See curves zone bag 0.25PSI, 0.18PSI in Figure 3.3 and zone bag 0.25PSI in Figure 3.4. Initial segments of these curves show that the zone bag does not conforming very well to the inner surface of the duct. However, at higher pressures the leakage seems to decrease. This could be due to reorientation of the zone bag owing to higher flow of air in the duct. This phenomenon seems to be random though. To avoid any ambiguity, it is suggested not to work at such low pressures in the zone bags

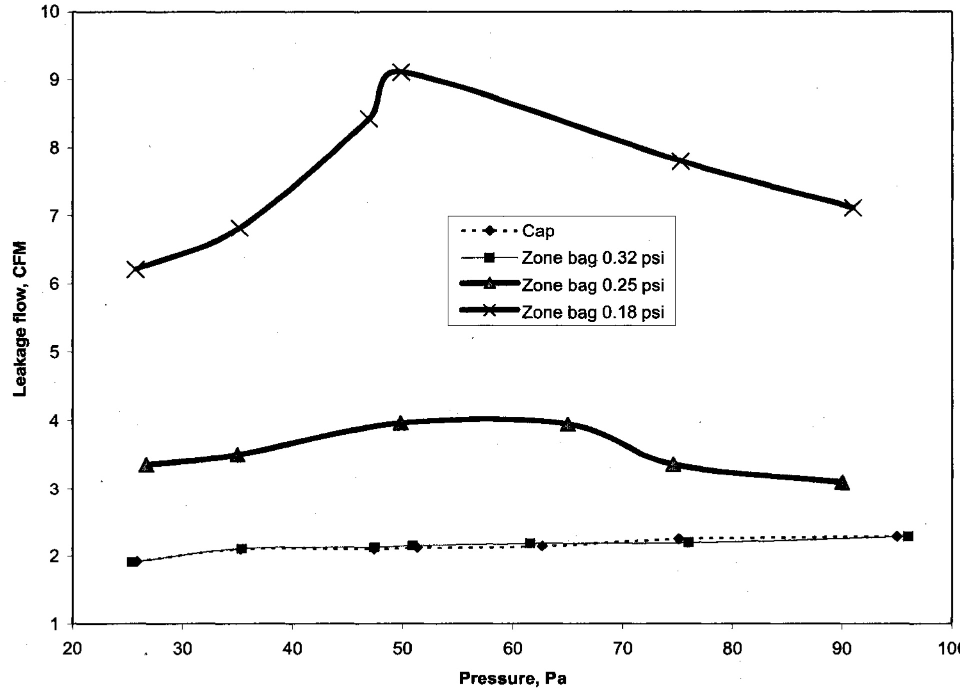

Figure 3.3 Effectiveness of the Zone Bags in Section of Straight 8" Duct for Different Pressures Inside the Duct and Zone Bags

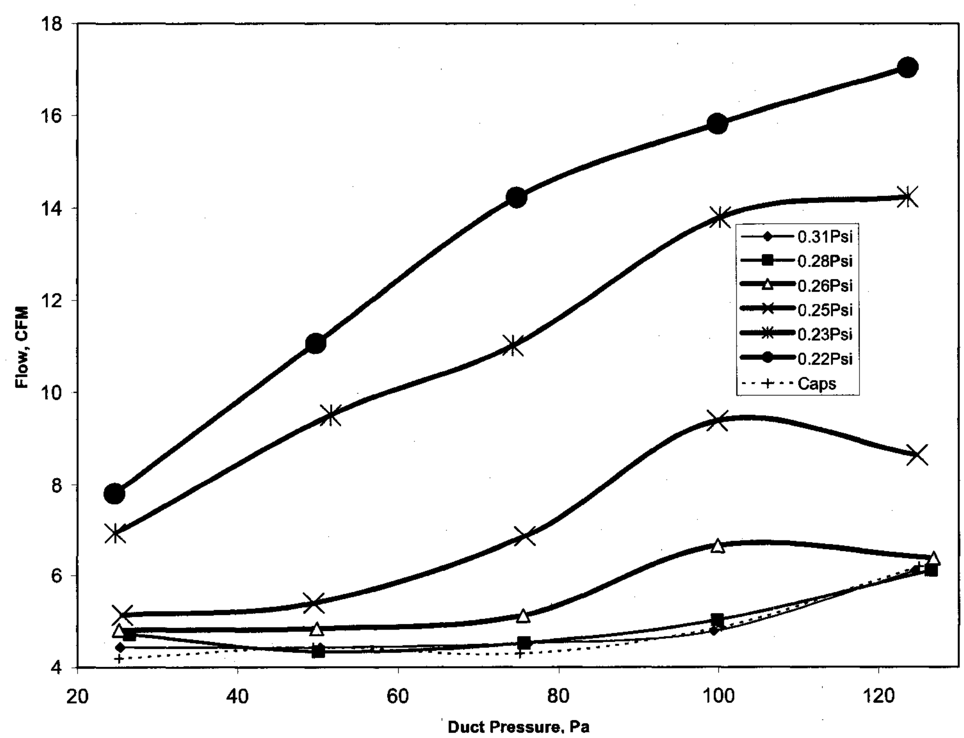

Figure 3.4 Effectiveness of the Zone Bags in Tee 8" Duct Section for Different Pressures Inside the Duct and Zone Bags

Table 3.1. Operational Range of Pressures for the Zone Bag

Duct diameter (Inches)	8”	10”	12”	14”
Pressure range (psi)	0.28-0.35	0.25 -0.30	0.23-0.28	0.19-0.22

3.1.3. Test Procedure

The Duct Pressurization Local leakage Technique (DPLT) proposed “local” leakage estimation is based on isolating sections of duct using zone bags. To isolate the investigated portion of duct, a zone bag is introduced into a section of the duct and inflated using compressed air. The pressure required inside the zone bags to block the flow of air was determined by parametric studies as discussed in the section 3.1.2. The leakage from each section is then determined by pressurizing it to multiple pressures (similar to the multipoint pressurization test). The relation between the leak flow and pressure is mapped to find local leak rates and leak locations.

The test procedure for DPLT is based on standard duct pressurization test that is part of ASHRAE Standard 152. It uses a calibrated fan to pressurize the duct to the required pressure. If a blower door is used to pressurize the house, the leakage will be leakage to outside as described in Annex B of the Standard. The calibrated fan could be attached at the register closest to the air-handler for pressurizing the supply side or at the closest return grill for pressuring the return side. It may also be attached at the air handler to pressurize either the supply or return side. In any case, a physical barrier should be placed between supply and return plenums to separate the supply side from return side.

In this study, a blower door was not used and therefore the leakage to inside was included. Owing to the small length of the return duct, the return side was treated as a single section and the aggregate return side leakage (not local) was determined for both air distribution systems. In addition, the calibrated fan was attached at the air handler to pressurize either the supply or return side.

Two different approaches could be used to determine the leakages in individual sections of ducts (Figure 3.5) using zone bags. The first approach was applied to ADS I in order to determine the leakage from the connections Y1, Y2, and Y3, the registers SR1, SR2, SR3, and SR4, and the supply plenum PL. The second approach was applied to ADS II in order to determine the leakages from the connection Y1, the registers SR1, SR2, SR3, SR4, and the supply plenum PL.

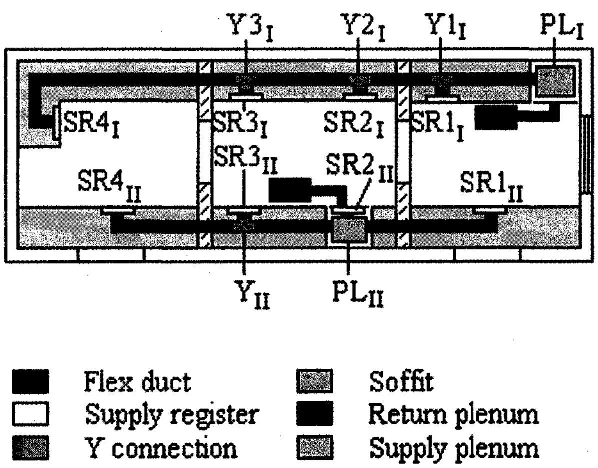

Figure 3.5 Floor Plan of the Test Facility With Designation

In the first approach (refer to Figure 3.6), a portion of the duct is blocked using the zone bag assembly. The leakage in this section (i.e. PL, step 1) is determined using the calibrated fan. The position of the zone bag is then changed to include another section of the duct (i.e. Y1, step 2). The cumulative leakage for these two sections at a specific pressure is estimated. The additional leakage thus found may be attributed to the later section. The same procedure is repeated for the entire length of the duct (step 3 for SR1, step 4 for Y2, step 5 for SR2, step 6 for Y3, step 7 for SR3, and step 8 for SR4).

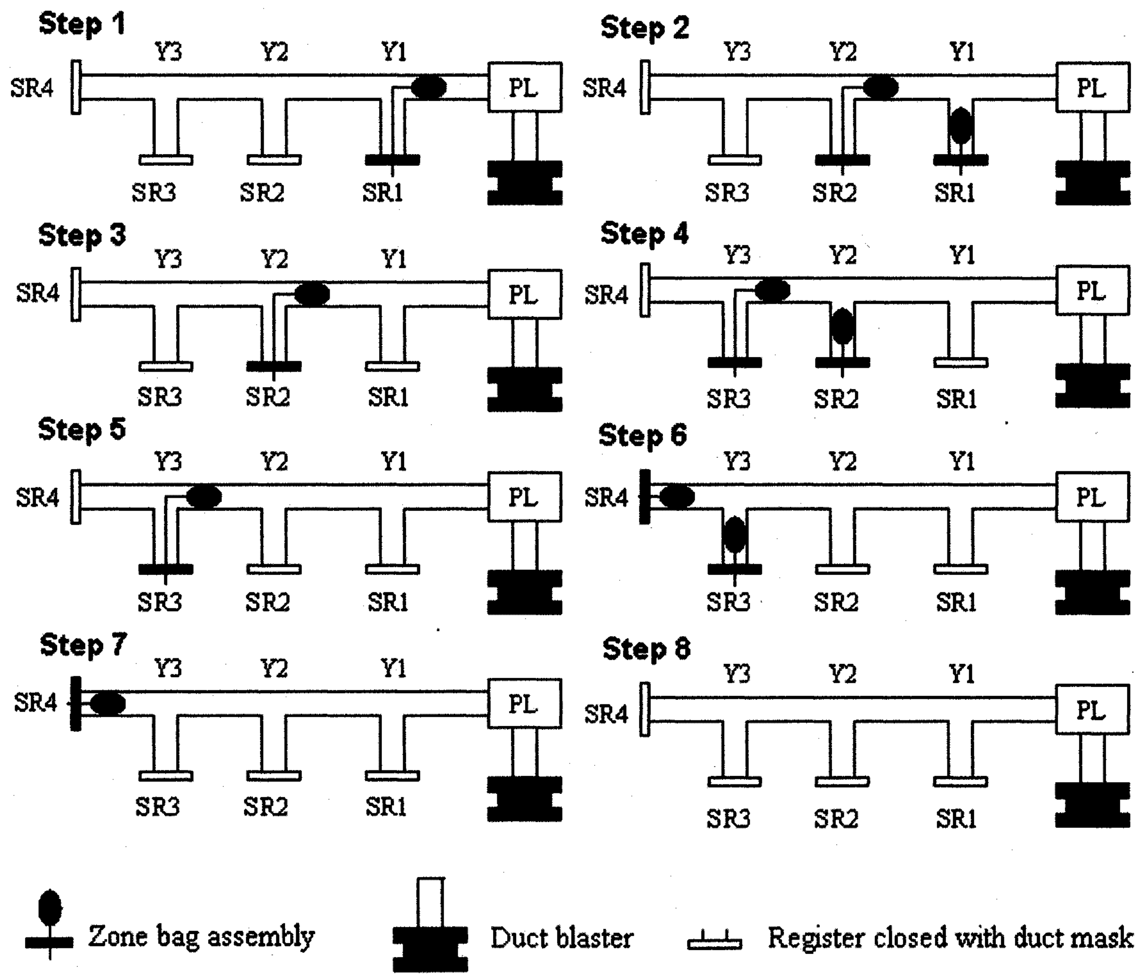

Figure 3.6 Steps for Determining the Local Leakages of ADS I

The alternative approach (refer to Figure 3.7) is to establish a baseline by conducting the standard duct pressurization test to find the total leakage (step 1). The duct mask or duct tape is removed from one of the registers (for instance the first register

SR1, step 2) and a zone bag is placed in the duct leading to this terminal boot. The pressurization test is now repeated. The decrease of flow through the calibrated fan is equal to the leakage in that particular register. The process is repeated sequentially for other registers and sheet metal connections (step 3 for SR2, step 4 for SR3, step 5 for SR4, and step 6 for Y). The leakage from the supply plenum PL is equal to the difference between the flow through the calibrated fan in step 1 and the sum of the local leak flows determined in step 2 to step 6.

The operating static pressures were obtained at various locations (i.e SR1, SR2, and etc). This was done with the air handler on and all registers open. These operating pressures were then used to determine the local leakages. Each step of both the approaches described above may be done either at one specific pressure (i.e. 25 Pa) or multiple pressures for more accuracy. For a single point test, the local leakage is determined by plugging the measured operating pressure value in the power law relation with an exponent of 0.6 (similar to the standard duct pressurization test). Whereas for a multipoint test, the pressure flow data is mapped. The local leakage is then obtained by interpolating for the measured operating pressure. Multipoint pressurization test was done for most of the tests discussed in this section unless mentioned otherwise. The results of this test will be discussed in section 5.1.

The ratio of pressure drops in the duct is equal to the square of the ratio of corresponding fan flows. However, the leak flow rate, when it is pressurized using a calibrated fan, is very small compared to the air flow when the air handler is on. If there is a 10% leak in a section of the duct and one were to assume that the static pressure in this section is constant, the change in pressure drop will be 0.1% and the error eventually

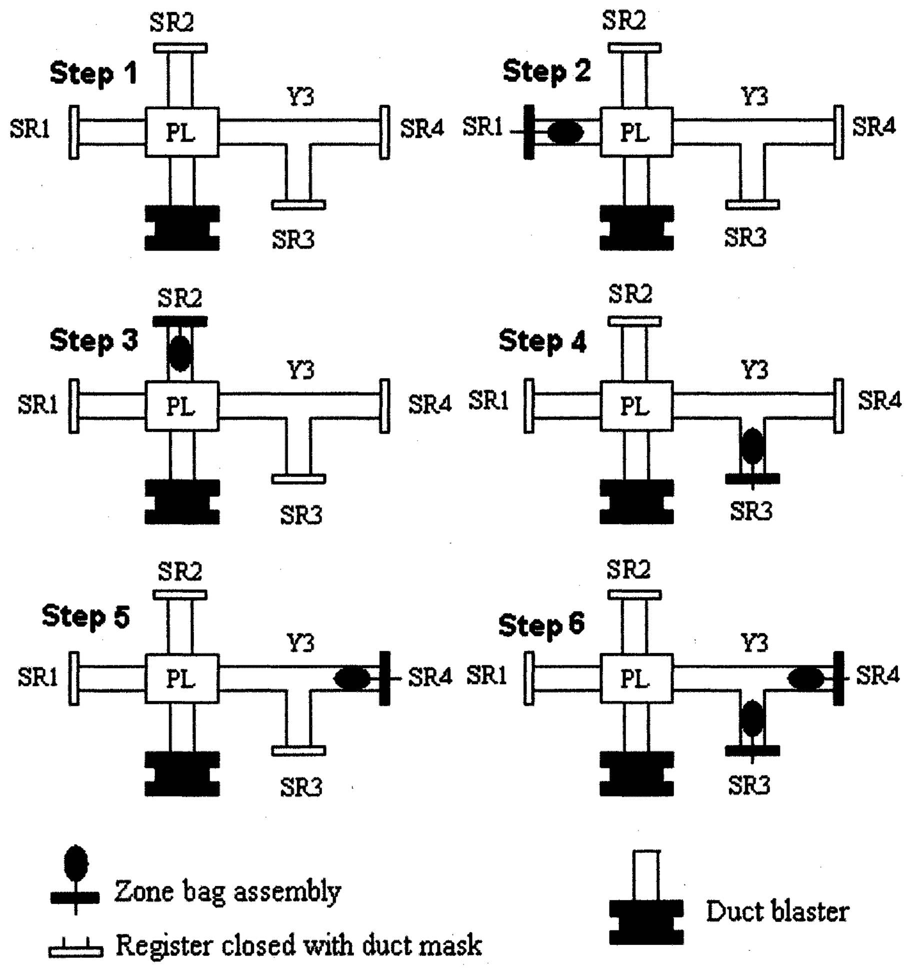

Figure 3.7 Steps Used for Determining the Local Leakages of ADS II

due to the assumption will be 0.01% which is negligible for the range of measurements being considered. This could therefore be as a reasonable approximation to avoid pressure measurements at each duct location which is time consuming.

3.1.4 Scope

DPLT has several advantages. These are

Local leakage estimation: Estimation of the local leakage provides can help in prioritizing the duct repair efforts to concentrate on most leaky locations.

Robustness: This technique has almost no restrictions on the type of system it can be used on, or the weather conditions during the test.

Simplicity: The results are easy to interpret without performing tedious calculations. The condition of the ducts can be evaluated without much effort.

Precision: The proposed technique reduces significantly the uncertainty associated with converting the leakage from the test pressure to the operating conditions, by estimating the local leakages and providing the opportunity to use directly the operating pressures for theses known locations.

Familiarity: Contractors that have performed envelope leakage tests are familiar with the test method, apparatus and calculation/interpretation methods.

The disadvantage with DPLT though is that the test requires all registers to be masked off and some of the registers opened to introduce the zone bag. This might be time consuming. On an average, for a home with ten supply registers, the maximum time required could be around 60 minutes.

3.2. Baseline

Apart from comparing the results of DPLT to the duct pressurization test, it was validated using a baseline. This was done by introducing controlled leaks (4.76 mm, 3/16" dia each hole) around the registers. This was also used as a baseline to validate the proposed DPLT. Also, additional leakage levels were tested by introducing artificial leaks in existing air distribution systems.

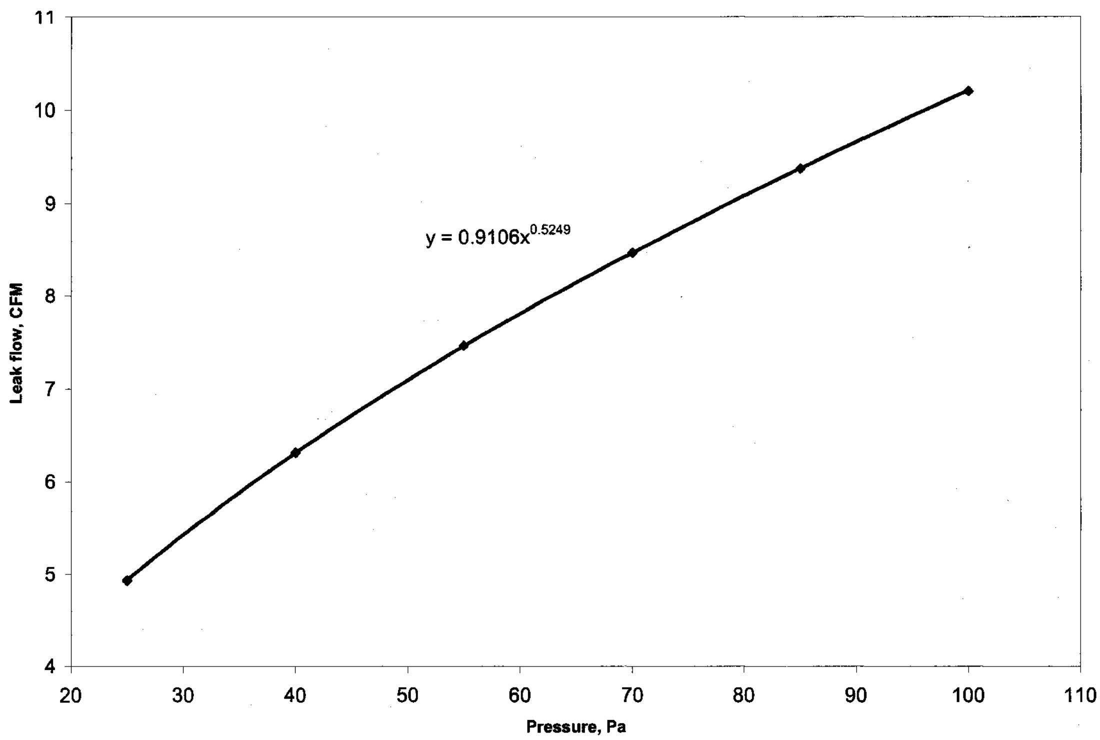

Figure. 3.8 Flow Characteristics of the 20 Holes Introduced in the Boot of the Registers

The artificial leaks were characterized by conducting the duct pressurization test before and after creating the leaks. At a particular pressure in the duct, the amount of change in the calibrated fan flow is equal to the leak flow from these holes. Figure 3.8 shows the flow characteristics of the 20 holes introduced on the boot of the register. There may be two sources of errors when the holes are being characterized: error from the method itself and error in the flow measurement. The first one is due to the fact that the change in the calibrated fan flow is not completely equal to the flow from additional holes. Although the static pressure near the holes is maintained constant before and after introducing the holes, the pressures in the locations between the holes and the calibrated fan may change slightly due to the variation of flow from the fan and therefore, a small variation in the leak flows. This effect could be reduced by characterizing the holes closer to the fan first and proceeding downstream. In this case, the static pressures were measured at several locations and leak flow was corrected for any change of the pressure before and after introducing the holes. Also, fewer holes were characterized initially so that there is a very small change in the flow before and after introducing holes. The second source of error is the flow measurement. This error was caused due to both precision and systematic errors. Since the leakages through the holes are measured by the change in the flow from the calibrated fan, the systematic error is canceled out. The precision error affects only the accuracy of leakage measurements. To improve the accuracy of this study, the tests were repeated several times and the average value of the leak rate for these holes was considered.

CHAPTER 4

CFD MODELLING OF DUCT LEAKAGE USING STAR CD

This chapter provides information on the simulation model as well as the simulation package and modeling process itself used for this work.

4.1 STAR-CD

Computational Fluid dynamics packages are now being widely used in industry and research alike to simulate phenomena like fluid flow, heat transfer and diffusion. The key feature of such packages is the ability to model complex models and generate accurate results consistently at a relatively low cost compared to experimental methods. These models can be used for predictive purposes in simulating physical processes where physical measurements are not possible or are very difficult or costly. With slight modifications in the numerical model, a range of configurations can be analyzed and different parameters varied if needed. A number of commercial codes are available. Some of them are STAR-CD, Fluent, ANSYS, PATRAN, Cosmos etc.

STAR-CD is a multipurpose thermo fluid analysis code. The solver provides numerical model solvers for both steady state and transient simulations. Some of the modules available in STAR CD are Pro-STAR, Pro-SURF and Pro-am. Pro-SURF is a surface preparation module. Proam provides a powerful meshing environment and a wide range of tools for other mesh repair needs. STAR-CD incorporates mathematical models of a wide range of thermo fluid phenomena including steady and transient; laminar and turbulent, incompressible and compressible. The mass and momentum conservation equations are solved by STAR-CD for general incompressible fluid flows in Cartesian tensor notation. Star CD offers extensive capabilities for viewing the results of the CFD analysis. Results can be viewed graphically or generated in the form of data tables. The graphical output can be generated in the form of vector plots, contour plots, particle tracks, graphs etc.

4.1.1 High Reynolds Number k-ε Model

For turbulent flows, the variables are linked to ensemble averaged flow properties in an analogous fashion to their laminar flow counterparts i.e. the mean continuity and momentum equations. There was no need to introduce the energy equation as the flow was expected to behave in an isothermal fashion. The k-ε high Reynolds number model (used here) in Star CD comprises of transport equations for the turbulent kinetic energy, k, and the dissipation rate, ε.

4.2 Model Description

This section presents the CFD models that were created and used for fluid flow simulation for determination of flow parameters for different leak geometries in ducts. The section describes the modeling methodology for the numerical models and running of these models for the specified conditions. All the models were simulated for 8" diameter duct of 60" length with the hole at the center of the duct (Figure 4.1). The 8" diameter was chosen as it one of the representative sizes of HVAC ducts in residential buildings. The assumptions used in the simulation are stated here. These assumptions hold good for all the models.

- The inner surface of the duct is assumed to be smooth and with no slip conditions.
- The flow is considered to be isothermal (293K), incompressible and turbulent.
- The inlet velocity is axial with the cross flow components set to zero.
- The molecular properties of the fluid are standard air properties (Table 4.1).
- The ambient pressure is 0 Pa gauge. This was acceptable because the fluid is treated as an incompressible fluid not being affected by any temperature changes.

Four hole geometries were considered in this study. They are:

1. 1" square hole
2. 1.5" X 1" rectangular hole
3. 3" X 1" rectangular hole
4. 1" dia circular hole
5. 1.5" X 1" (major axis X minor axis) elliptical hole
6. 3" X 1" (major axis X minor axis) elliptical hole

For the first three models, the trimmed cell mesh was generated in Pro Star itself. Therefore these models did not require surface checks. Volume refinements in areas around the leak and layers near the duct wall where high gradients were expected were refined using Pro Star tools (Figure 4.2). For the other three models, the model geometry was built in Solidworks. This was imported into Pro surf to check and repair any possible surface errors. The surface of the resultant model was then triangulated using an inbuilt function. A volume mesh was generated at this stage. Pro-am also provides tools for local refinement in areas of higher gradients: in this case the area around the leak and cell layers adjacent to the duct walls. Local surface property settings were used to specify the refined cell size and volume based refinements was used to obtain refinement zones (Figure 4.3). Trimmed cells were used for volume mesh and cell quality checks were performed on the resultant volume mesh.

Five different values of Reynolds numbers were simulated for all the models, i.e., 0.27 X 10^5, 0.41 X 10^5, 0.55 X 10^5, 0.69 X 10^5 and 0.82 X 10^5 to simulate a variety of flows that are possible in residential air distribution systems. These correspond to inlet velocities of 400fpm to 1200fpm which are representative of the typical velocities in residential HVAC ducts. The inlet axial velocity was assumed to be uniform with all cross flow components set to zero. No slip condition was imposed on the inner wall. The molecular properties of the fluid are standard air properties (Table 4.1). It has been found that the standard k-ε produces best results for pressure distribution in ducts (Launder et al., 2004; Gan et al., 1999). The high Reynolds k-ε model was used for CFD simulation of all the duct models. Parameters of the k-ε high Reynolds number model are mentioned in Table 4.2. *K* and *ε* were assumed to be 0.0035 and 0.012 respectively.

Table 4.1 Molecular Properties of Fluid

Density	1.205 kg/m^3
Molecular viscosity	1.81e-05kg/ms

Table 4.2. Coefficients of the Standard k – ε Turbulence Model

C_μ	σ_k	σ_ε	σ_h	σ_m	$C_{\varepsilon 1}$	$C_{\varepsilon 2}$	$C_{\varepsilon 3}$	$C_{\varepsilon 4}$	κ	E
0.09	1.0	1.22	0.9	0.9	1.44	1.92	1.44	-0.33	0.419	9.0

These values were used as the default values (STAR CD user manual) suggested by the user manual) as no other experimental data was available to fine tune these values.

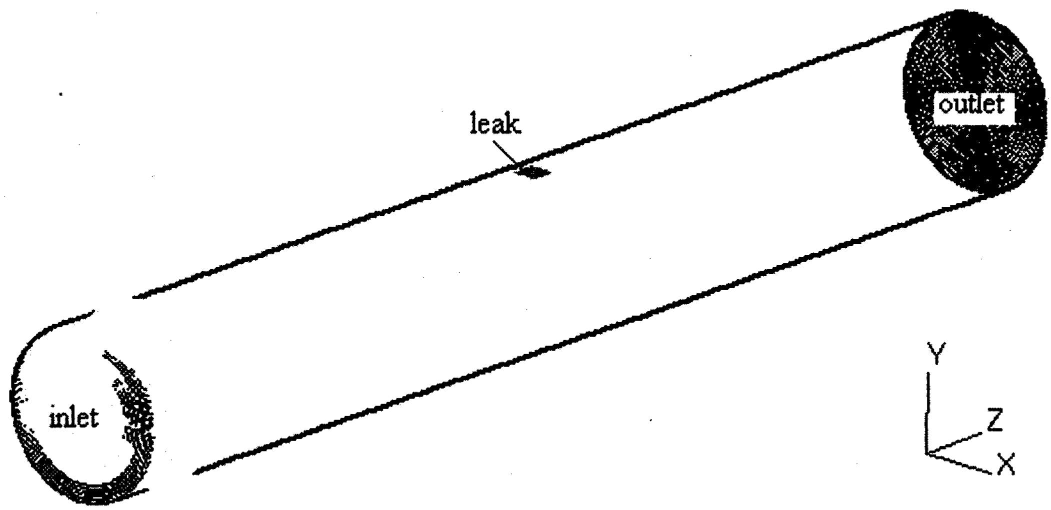

Figure 4.1 Model of Duct for Simulation with Boundary Conditions

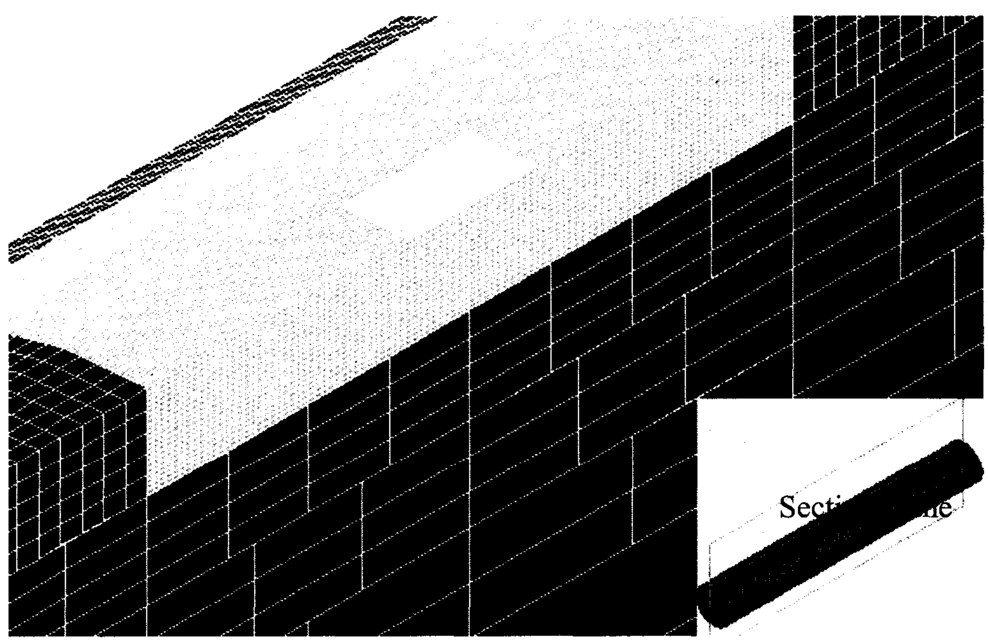

Figure 4.2 Isometric Sectional View: Computational Domain for Duct with Square Hole

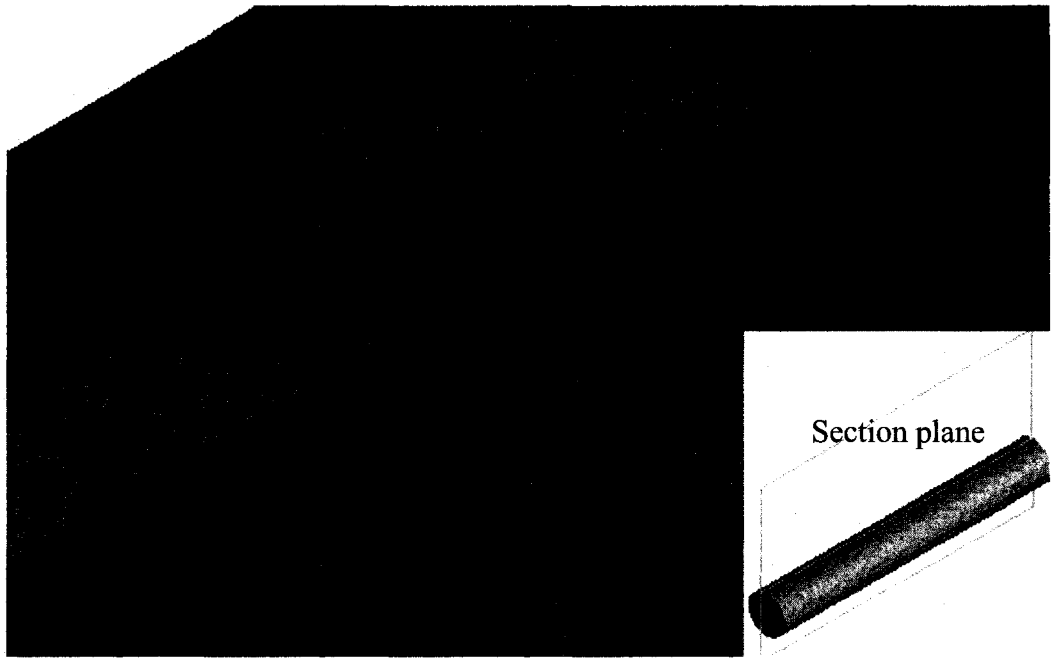

Figure 4.3 Isometric Sectional View: Computational Domain for Duct with Circular Leak

This stage involves the actual computation of the mesh and boundary conditions. Proper understanding of the nature of the flow is necessary to choose the appropriate mathematical model and numerical solution algorithm. All simulations were done in steady state. The default algorithm SIMPLE was used as the solution algorithm. A tolerance of 1.0 X 10^{-4} was used for convergence.

CHAPTER 5

RESULTS AND DISCUSSION

This chapter provides the results of the experimental tests and the CFD simulations.

5.1 Experimental Test Results

The Duct Pressurization based Local leakage Technique (DPLT) was applied to ADS I and II to determine the local leakage in different locations of the supply duct and the total leakage from the return duct. Two sets of tests were conducted: (i) to find the actual local leakage in the ducts and (ii) to find the leak rates from artificial holes introduced at various locations in the duct. The tests was verified qualitatively by smoke testing and quantitatively using the baseline.

As mentioned earlier, the flexible ducts were installed to resemble typical residential installations in the Las Vegas area. The first set of tests was done on air distribution systems to find the inherent leaks in the system due to faulty installation. The DPLT tests were performed as mentioned in section 3.1.3 for both systems (Figure 3.6 and 3.7). Each duct section was pressurized to multiple test pressures. Figures 5.1 and 5.2 depict the local leakage as a function of the duct pressure for ADS I and II respectively. The leakages in sheet metal connections (Y1, Y2, and Y3) were low (about

3 CFM) and hence are not shown on the graph. To determine the local leakage under operating conditions, the static pressures are measured in each duct section studied and the local leak rates were interpolated from the graph values. For instance, the operating pressure in the supply plenum for ADS I was 30 Pa. The multipoint DPLT curve for this section of the duct is shown in Figure 5.1. From this curve the leakage corresponding to 30 Pa is 16.50 CFM. Expressing this as a percentage of total air handler flow (750 CFM) gives 2.06% leakage in the supply plenum for ADS I. A similar approach was followed for the remaining sections of the duct. The results are listed in Table 5.1.

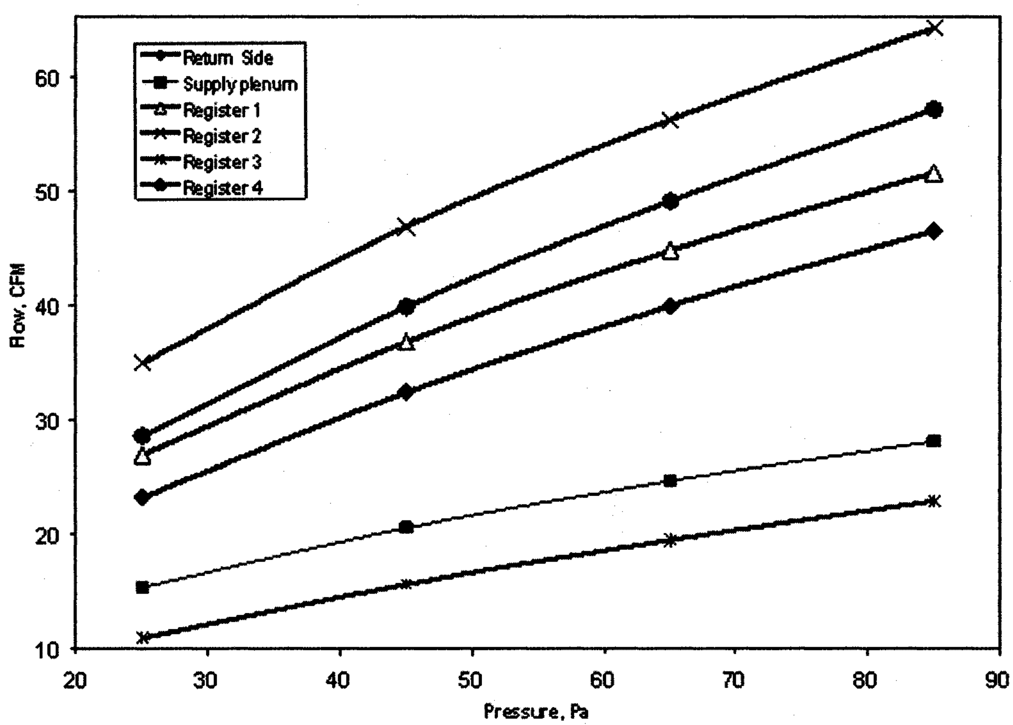

Figure 5.1 Local Leakages as a Function of Pressure in the Duct Section for ADS I

The leakiest locations were identified to be PL, SR1, and SR2 for ADS I and PL and SR1 for ADS II (Table 5.1). This was confirmed qualitatively by conducting a smoke test. By visual inspection it was found that the leakage in SR1 and SR2 was due to a wide space left between the lateral face of the boot and the dry wall. Sealing these accessible leaks (SR1 and SR2) for ADS I, led to 3.7% reduction in the total leakage.

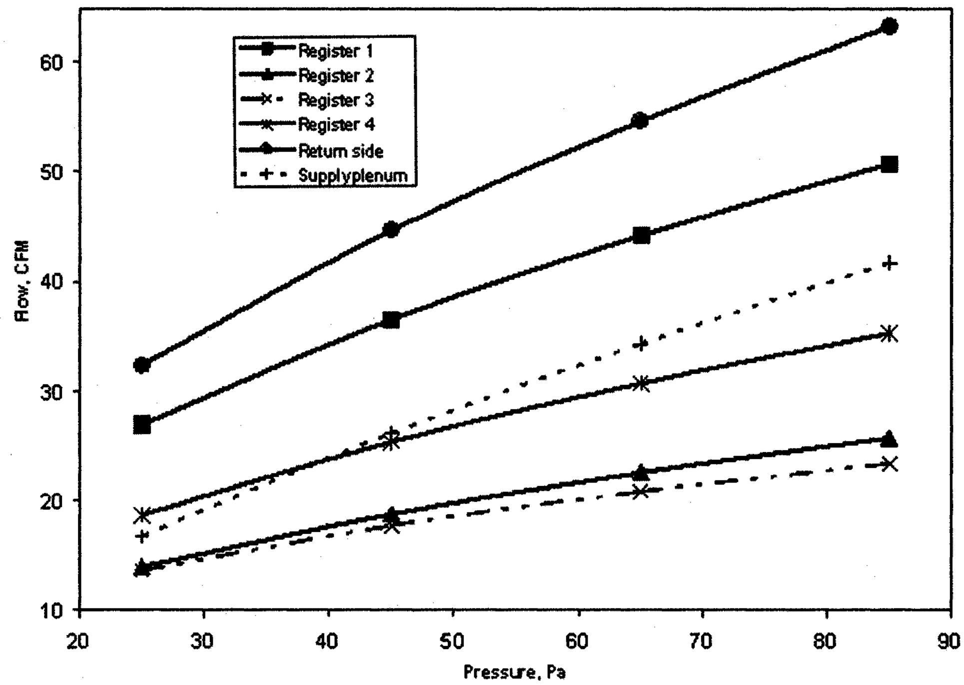

Figure 5.2 Local Leakages as a Function of Pressure in the Duct Section for ADS II

Table 5.1. Local Leakage in Different Duct Sections

	PL	SR1	SR2	SR3	SR4	Y1	Y2	Y3	RS[a]	SS[b]
Leakage % for ADS I	2.06	1.42	1.75	0.37	0.85	0.62	0.44	0.25	3.44	7.76
Leakage % for ADS II	1.81	1.63	0.78	0.75	0.70	0.55	-	-	7	6.2

a. RS: Return side

b. SS: Supply side, determined as a sum of local leakages

As mentioned in section 3.1.2, parametric studies were conducted to verify that the zone bag blocks the flow of air in the duct completely. Even if we assume that there is some leakage due to inadequate seal between the zone bag and the duct, the leakages in duct sections will be underestimated and the leakage in supply plenum overestimated. For example, the leak rate from SR1 in ADS II at the register (see Figure 3.5) will be underestimated and then the supply plenum leakage will be somewhat overestimated. In extreme cases, when the zone bag is unable to block the flow of air in the duct, the leakage in locations other than the plenum will be found to be zero. Then the leakage determined by the proposed zone bag-based technique will be the same as the duct pressurization test using the plenum pressure technique.

For a more detailed analysis of the proposed method it is imperative to work with a wide range of leakage levels. The second set of tests was conducted by introducing artificial leakages at several location of the duct. The number of holes introduced was varied from 1 to 40 at each terminal boot i.e., the artificial leakage was varied between 1% and 6% of total flow. The flow through the holes was characterized as described in section 3.2. In addition, the local leaks identified by the first set of tests (Table 5.1) were sealed very well except for the leaks in the supply plenum. Figure 5.3 shows the leak rate from each register as determined by the baseline and the proposed Duct Pressurization based Local leakage Technique (DPLT). The diagonal line is a one to one line and indicates the agreement between the values obtained by the baseline and proposed techniques. The mean difference between the baseline and the proposed techniques is 0.05%. This shows that there is very little bias. The scatter is relatively low with a mean absolute difference of about 0.26 % of total air-handler flow. Therefore it can be concluded that the proposed technique estimates the local leak rates accurately.

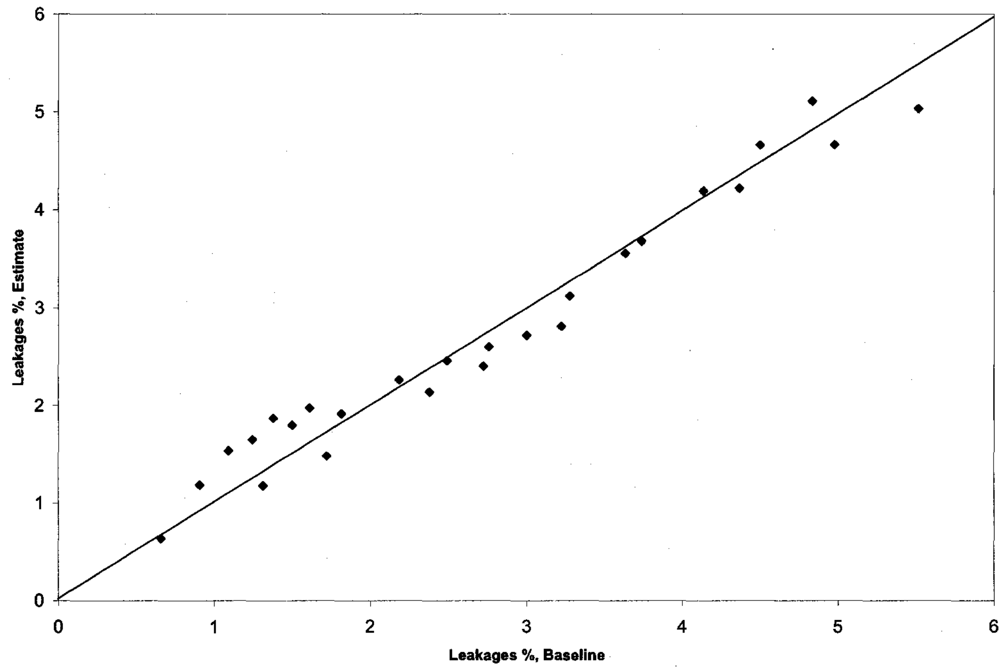

Figure 5.3 Leak Rates in the Registers as Determined by the Baseline and DPLT

In addition, the total leakage estimated by the proposed technique and that estimated by duct pressurization test was compared with the baseline (Table 5.2). The mean difference between the baseline and DPLT is -0.07% and between the baseline and duct pressurization technique is 0.1. The mean absolute differences are 0.09% and 0.6 % for the proposed and duct pressurization test techniques, respectively. That indicates that the proposed technique gives a better estimate of the leakage than the duct pressurization technique. This is mainly because the proposed technique uses the operating leak pressures to estimate the leakage at different portions of the duct.

Another aspect to be discussed here is the error in flow measurement. Since the leak flows are measured by the calibrated fan (Minneapolis Duct Blaster B), the error is related to the accuracy of the flow measurement. The systematic (bias) errors obtained by measuring the local leakages using the proposed technique will cancel out as changes in flow from the calibrated fan is being considered, with the exception of the plenum leakage (see step 1 in Figure 3.6). The systematic error from the proposed technique however is less than that from the duct pressurization test.

Table 5.2. Total Supply Leakage: Baseline, DPLT and Duct Pressurization Technique

Baseline Leakage % BSL	DPLT leakage % DPLT	Pressurization test Leakage, % PT	Difference % BSL-DPLT	Difference % BSL-PT
3.80	3.84	2.62	-0.04	1.18
4.27	4.20	3.42	0.07	0.85
4.68	4.68	3.87	-0.01	0.81
5.02	5.19	4.46	-0.17	0.56
5.33	5.40	4.89	-0.06	0.45
5.73	5.84	5.81	-0.11	-0.08
6.22	6.25	6.31	-0.03	-0.09
6.84	6.87	7.08	-0.03	-0.24
7.06	7.02	7.39	0.04	-0.33
7.54	7.70	8.23	-0.16	-0.70
8.24	8.51	9.54	-0.27	-1.30
Max difference			0.27	1.18
Mean difference			-0.07	0.10
Mean absolute difference			0.09	0.60

For a 1% bias in the flow reading, the error for the proposed technique occurs only for the plenum and is 1% of the leakage in the plenum (i.e. 0.2% of total flow for ADS I). However, the bias from the duct pressurization test is 1% of the total leakage (i.e. 0.77%

of the total flow for configuration I). Thus the systematic error from the proposed technique is lower than that from the duct pressurization test. This is an added advantage.

5.2 CFD Simulation

5.2.1. Grid Independency Results

While creating models with CFD codes it is important to check whether the solution is independent of the grid. One way to perform this study is to increase the number of grids in the model and resolve the model. The solution from two models of different grid densities is compared. One or several such comparisons can be done to ensure grid independency. If the solutions of the two grids are within a sufficiently small predetermined tolerance, the original grid density is sufficient.

The effect of grid density on the results for the current models was determined by performing a grid independency study. This was done by increasing the number of grid lines in each of the dimensions and monitoring the solution. Grid independency tests were carried out for the Y component of velocity over the width of the hole (Figure 5.4), Y and Z component of velocity over the height of the hole (Figures 5.5 and 5.6). Grid 1 is the coarsest grid and grid 5 is the finest grid with about 800000 cells. It was found that the average variation in the velocity component magnitude, in the Y direction along the width of the leak was not more than 0.003% from grid 4 to grid 5. The average variation in the velocity component magnitude, in the y direction along the height of the leak was not more than 2.1% and in the Z direction along the height of the leak was not more than 0.19% from grid 4 to grid 5. Grid 4 was therefore considered to be sufficient for all the numerical calculations. Due to the volume of the work undertaken, and as all the models had the same physical dimensions, grid sensitivity studies were not undertaken for all the models and all the cases.

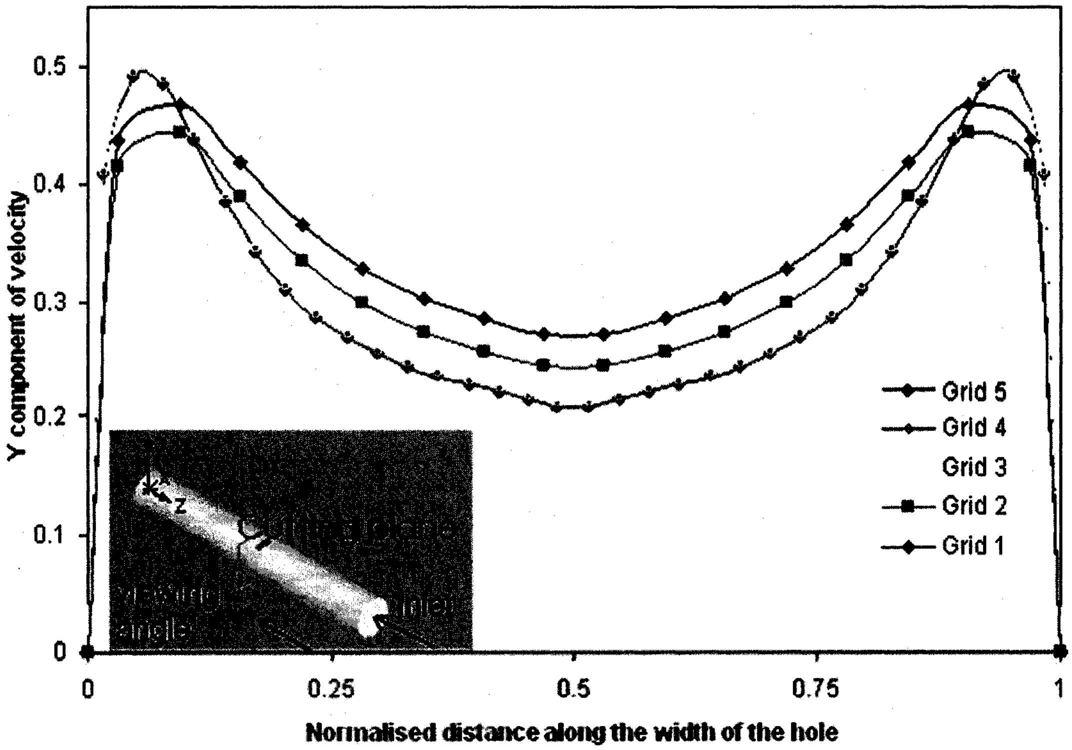

Figure 5.4 Y Component of Velocity [m/s] at the Leak Cross Section in XY Plane

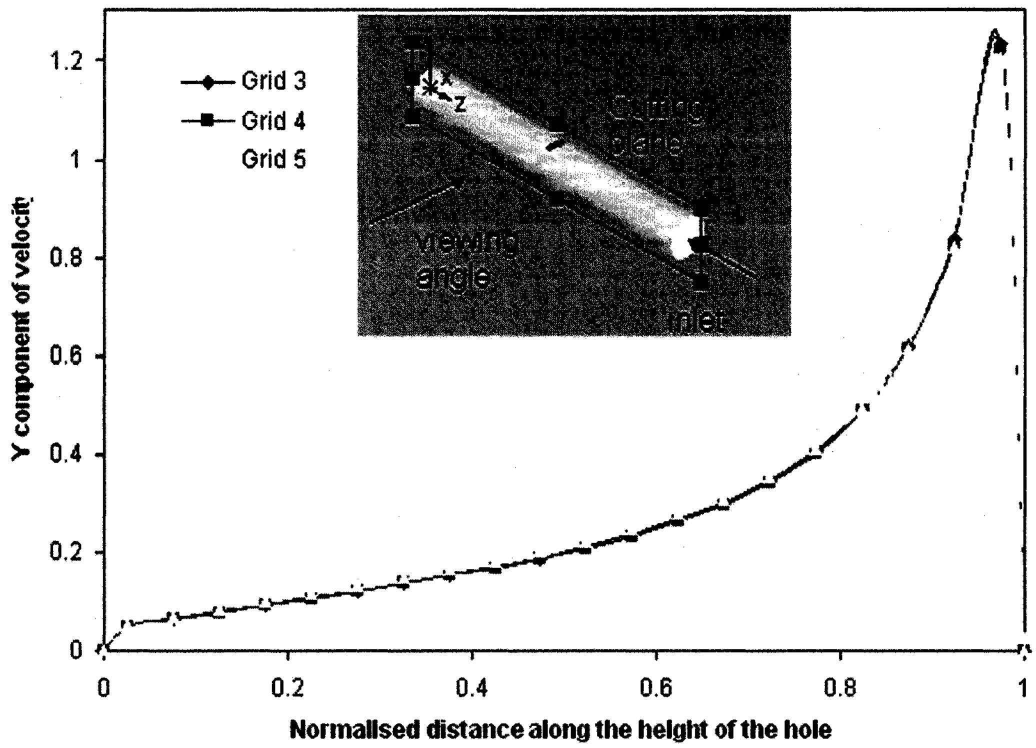

Figure 5.5 Y Component of Velocity [m/s] at the Leak Cross Section in YZ Plane

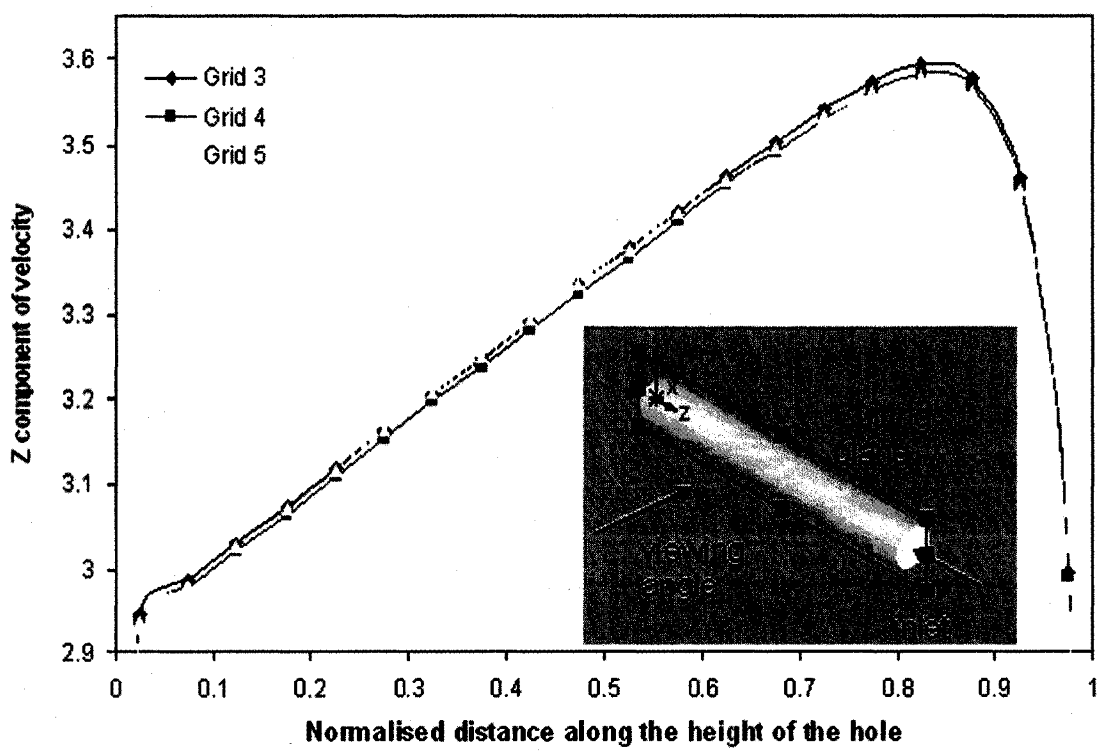

Figure 5.6 Z Component of Velocity [m/s] at the Leak Cross Section in YZ Plane

5.2.2. CFD Simulation results

STAR-CD a CFD code was used to predict airflow and pressure distribution in the duct models using different leak geometries and over a range of Reynolds numbers to gain a better parametric understanding of the relationship between leakage flow and pressure drop across these leaks. Six generic geometries of potential leaks were used i.e. square, rectangular, circular and elliptical shapes. This section deals with the results of these models.

Figure 5.7 shows the static pressure distribution in a duct with a rectangular leak (with an aspect ratio 3) and with an inlet velocity of 400 fpm (Re 27000). The static pressure drop pressure along the length of the duct decreases in the flow direction owing to frictional loss. The static pressure drop in the duct at different cross sections in the flow direction has been plotted in Figure 5.8. The average static pressure drop at each section was calculated as the area average of the static pressure drop of the cells lying on that particular section. The slope of the line AD is -0.52 and that of line GI is -0.3 (see 5.8). The change in the slop indicates that the flow is not completely developed.

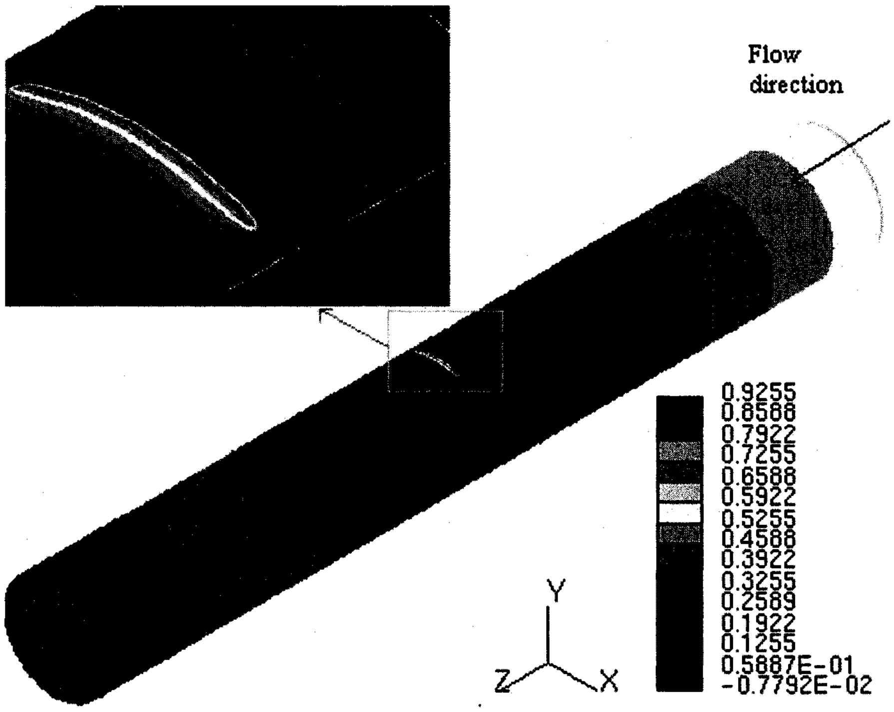

Figure 5.7. Static Pressure Drop along the Duct Length [Pa]

The pressure distribution in the area of the hole and in its vicinity does not follow this trend as the hole is exposed to atmospheric pressure transversely, in this case 0 Pa gauge. The pressure loss due to the hole is higher than the frictional loss along the length of the duct as the distance between the center of the duct to the outside of the leak is small compared to distance to the outlet where a 0 Pa pressure boundary condition has been imposed. The bump in the graph indicates the sudden surge in pressure loss due to the leak (Figure 5.8). The flow separation and hence loss of momentum causes a large pressure drop at the leak. Also, from the graph it is evident that the static pressure drop between points E and F is almost constant. The flow at the leak moves suddenly into a large opening. Some portion of the dynamic pressure is thus transformed to static pressure at this stage, the overall effect shows that the static pressure is constant.

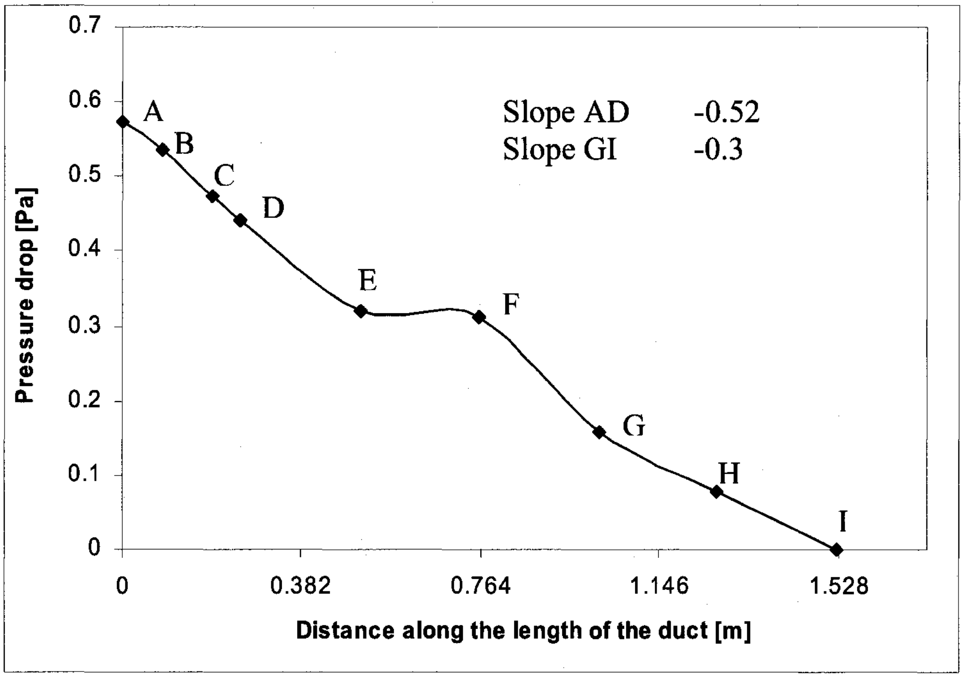

Figure 5.8. Frictional Pressure Loss Vs Static Pressure Loss due to the Leak

The leak is exposed to a lower pressure than that of the duct, and hence the flow tries to exit out of the leak. However, the flow is subject to some inertia before it tries to exit out of the leak. The velocity components of the flow from the leak are therefore maximum only around the trailing edge of the leak (Figure 5.9). Also, the trailing edge of the leak however is subjected to higher pressures due to the momentum force of the exiting air stream (Figure 5.7).

The Y component of velocity at the center of the leak is as shown in Figure 5.10. Due to the no slip condition at the walls, the velocity at those points goes to zero. The velocity peaks in this graph are due to the X component of velocity that acts towards the center of the hole due to the immediate pressure boundary condition at the leak. This is evident from Figure 5.11.

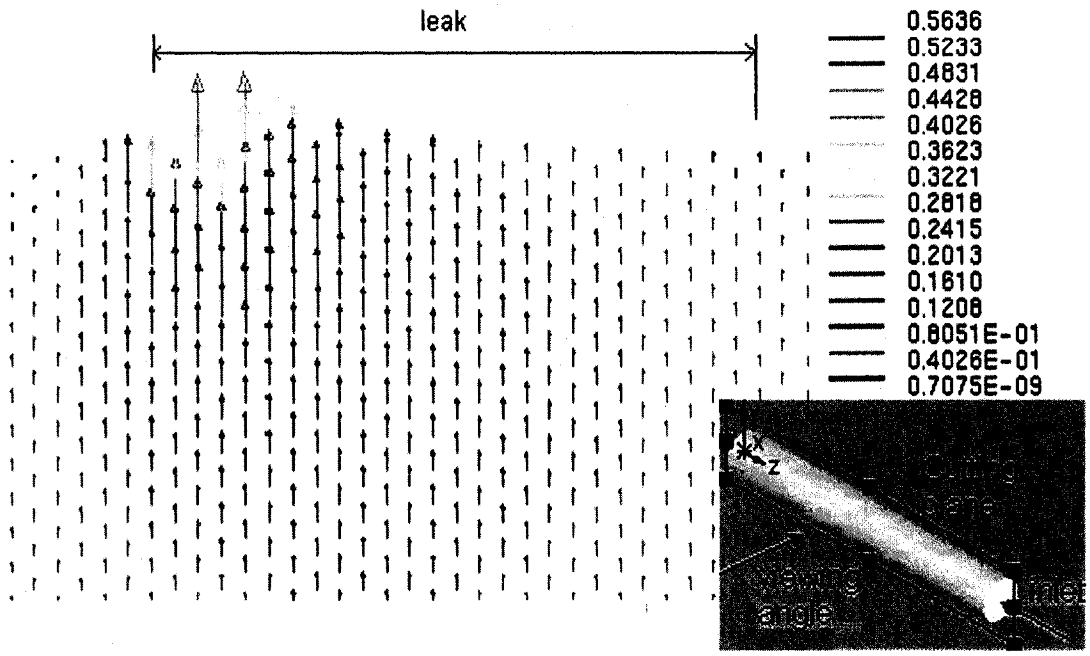

Figure 5.9 Y Component of Velocity [m/s] at the Leak Cross Section in YZ plane

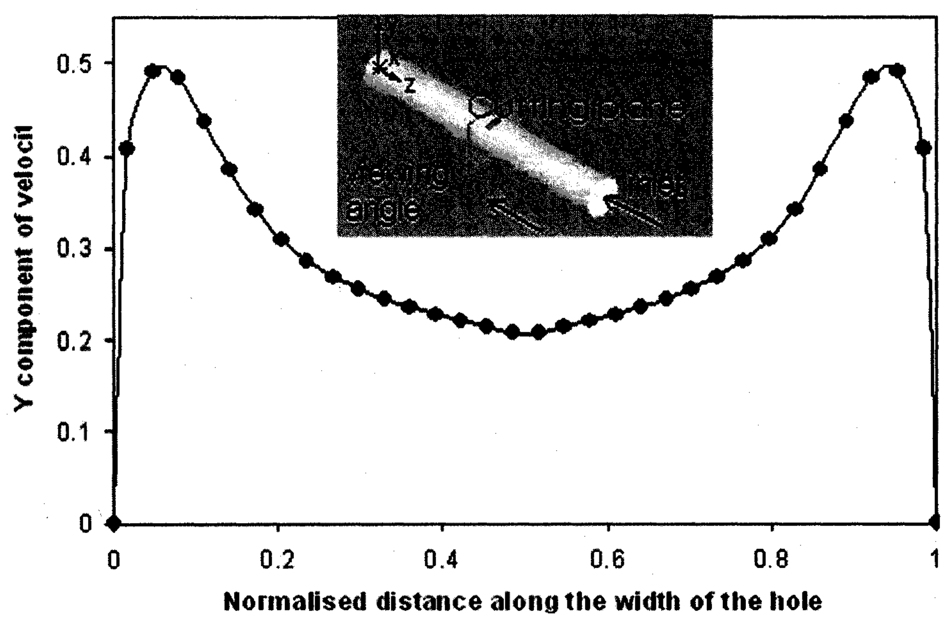

Figure 5.10 Y Component of Velocity [m/s] at the Leak Cross Section in XY plane

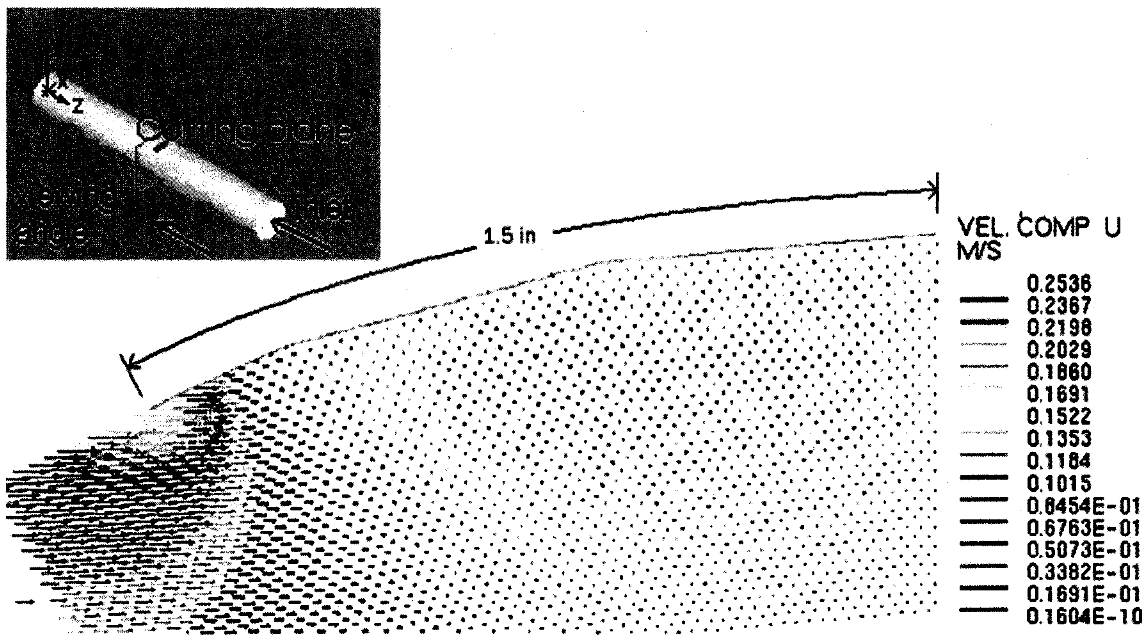

Figure 5.11 X Component of Velocity [m/s] at the Leak Cross Section in XY plane

5.2.3. Power Law Model

The functional form of pressure flow relationship can be used to characterize a leak. The power law relationship has the form

$$Q = C \times \Delta P^{n} \qquad (5.1)$$

where, Q is the flow rate through the hole, m^3/s

ΔP is the average static pressure drop

C is the flow coefficient, $m^3/s\ (Pa)^n$

n is the pressure exponent, dimensionless

The power law leakage model provides a convenient method to predict the leakage flow of a duct system when reliable values for C and n are available. The power law formulation has gained almost universal acceptance for leakage measurements in ducts (Aydin et al., 2006).

The objective of the CFD simulations is to obtain reliable values of C and n that can be used to predict the flow in the duct for a particular geometry and size of leak. All the models for duct leakage were simulated using five different Reynolds numbers ranging from 0.27 X 10^5 to 0.82 X 10^5. ΔP in this case is the average static pressure at the duct cross section in the XY plane passing through the center of the leak. The static pressures and the face areas of all the cells lying on this cross section were obtained from the CFD model. ΔP was calculated by taking the area average of static pressures of all the cells on that cross section.

$$Q = A_{leak} V_{mean} \tag{5.2}$$

Where, Q is the air flow through the leak, m^3/s

V_{mean} is the mean normal velocity through the leak

A_{leak} is the surface area of the leak.

Y component of velocities and the face areas of the cells on the surface of the leak were obtained from the CFD model and V_{mean} was calculated by taking the area average of Y component of velocities of the cells on the surface of the leak. Values for Q and ΔP for each case were then fitted (Figure 5.14) using a simple curve fitting model. Each of the curves thus fitted has the form of the power law model (see the power law equation for the rectangular leak of aspect ratio 3 in Figure 5.12). For instance, the flow coefficient, C and pressure exponent, n for the rectangular leak of aspect ratio 3 are 0.006 and 0.4409 respectively. The values of flow coefficient and pressure exponent for each of the leak geometries are listed in Table 5.3. Existing tests assume that the value of pressure exponent to be 0.6(Walker et al. 2002)

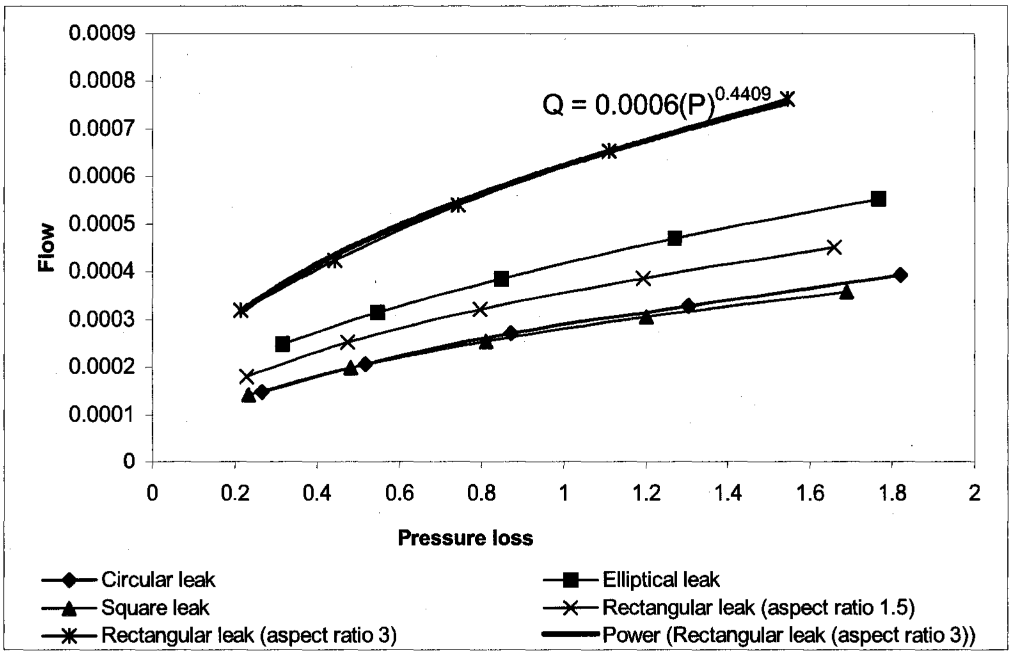

Figure 5.12. Characteristic curves for leak geometries

Table 5.3 Values of C and n for different leak geometries

Leak geometry	Pressure coefficient C	Leak exponent n
Square leak	0.0003	0.4618
Rectangular leak (aspect ratio 1.5)	0.0004	0.4623
Rectangular leak (aspect ratio 3)	0.0006	0.4409
Circular leak	0.0003	0.5028
Elliptical leak	0.0004	0.4644

According to previous studies, the leakage through a discrete rupture in the duct may be approximated by the equation of a regulator (Auld, 2004, Le Roux, 1979 and Howe, 1995) as follows:

$$Q_{leak} = \frac{A}{\rho_{std}}\sqrt{\frac{\Delta P}{\rho_{act}}} \tag{5.3}$$

where Q_{leak} is the leakage, m^3/s

A is the area of the leak, m^2

ρ_{std} is the density of standard air, 1.205 kg/m^3

ρ_{act} is the density of air

ΔP is the static pressure differential across the wall

ΔP values from the CFD results were used to calculate Q_{leak} from equation 5.3. It was found that there was an absolute error of about 49% when one uses this formula to calculate the Q_{leak} when compared to the values from the CFD solution. To reduce this error a correction factor of 0.5 could be used and the formula would be

$$Q_{leak} = CF\frac{A}{\rho_{std}}\sqrt{\frac{\Delta P}{\rho_{act}}} \tag{5.4}$$

where CF is 0.5

Calculating the Q_{leak} yielded an absolute error of about 4.6%.

If the ΔP is measured and the area of leak is known, one can use equation (5.4) to calculate Q_{leak} more accurately.

5.2.4. Pressure Loss Coefficients

The energy loss in the duct due to leakage is assessed using a parameter called pressure loss coefficient or k factor (Gan et al., 1999). The k-factor for the leaks is defined as

$$k = \frac{\Delta P_s}{\frac{1}{2}\rho V^2} \tag{5.5}$$

where, k is the pressure loss coefficient or k-factor

ΔP_s -is the static pressure loss due to the leak with respect to ambient pressure, Pa

V -is the mean velocity of the air flow through the leak, m/s

The pressure distribution and hence the k- factors for each of the leak geometries for the range of Reynolds numbers were calculated and are listed in the table below (Table 5.4).

Table 5.4 Values of pressure loss coefficient for different leak geometries

Reynolds number	Pressure loss coefficient or k- factor					
	Square leak	Rectangular leak (aspect ratio 1.5)	Rectangular leak (aspect ratio 3)	Circular leak	Elliptical leak (aspect ratio 1.5)	Elliptical leak (aspect ratio 3)
27000	11.52	13.64	19.96	4.8	4.7	5.97
41000	12.24	14.5	23.47	4.95	5.08	6.48
55000	12.71	15.02	24.32	4.84	5.24	6.76
69000	13.07	15.48	24.94	4.94	5.3	6.85
82000	13.41	15.85	25.48	4.82	5.33	6.91

Table 5.5 Ratio of area and perimeter for different leak geometries

Leak Geometry	Area/Perimeter [m]
Square leak	0.0065
Rectangular leak (aspect ratio 1.5)	0.0076
Rectangular leak (aspect ratio 3)	0.0095
Circular leak	0.0060
Elliptical Leak (aspect ratio 1.5)	0.0075
Elliptical Leak (aspect ratio 3)	0.0085

The ratio of area and perimeter is proportional to the frictional force or the wall shear stresses encountered by the flow through an opening. This ratio for a circular leak is lower than that of a square leak (Table 5.5). The mean velocities through the leak are thus lower for a circular leak than for a square leak. K- factor is inversely proportional to the square of the mean velocity through the leak. Therefore the k-factor for the circular leak is less than that of the square leak. The predicted *k*- factors are found to increase monotonously with increase in aspect ratio of the leak (Figure5.13 and 5.14).

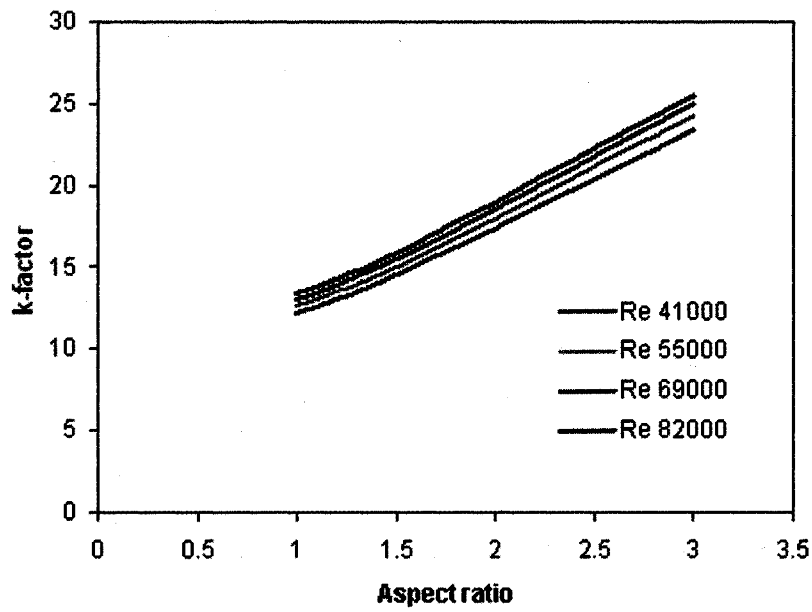

Figure 5.13. Aspect Ratio Vs *k*- factors for Square Leaks

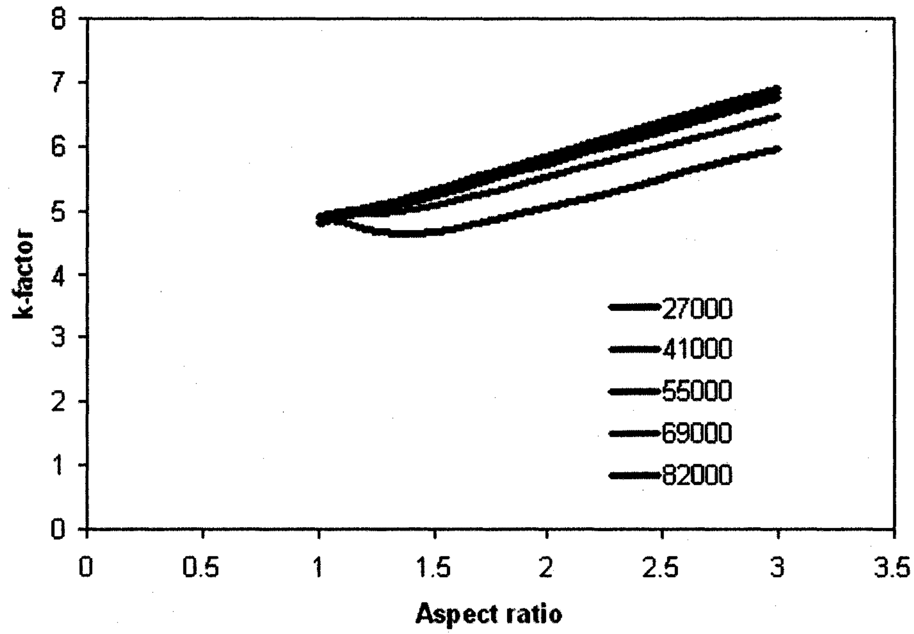

Figure 5.14. Aspect Ratio Vs *k*- factors for Circular Leaks

For the range of Reynolds numbers simulated it was found that the static pressure drop was fairly constant with change in aspect ratio of the leak (Figure 5.15). It appears that the mean velocity through the leak reduces with increase in aspect ratio (Figure 5.16). This can again be attributed to the increase in frictional forces with the increase in aspect ratio. The pressure loss coefficient is therefore a function of the geometry of the leak.

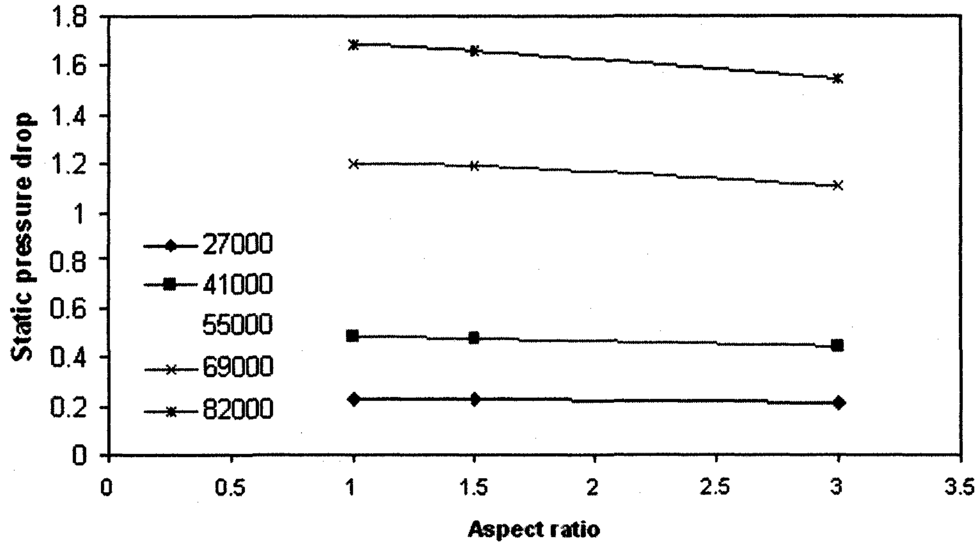

Figure 5.15 Aspect ratio Vs Static pressure drop for rectangular leaks

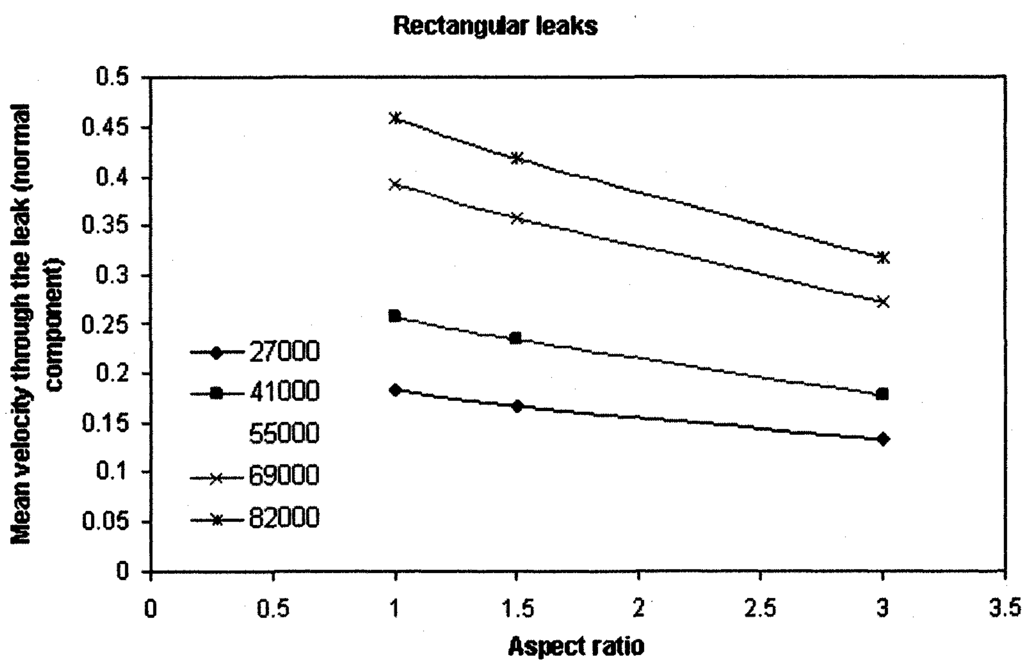

Figure 5.16 Aspect ratio Vs Mean Velocity through the leak for rectangular leaks

CHAPTER 6

CONCLUSIONS

6.1. Experimental Work

The DPLT technique for local duct leakage estimation was validated at the ADLL on two air distribution systems with wide range of leakage levels controlled by holes created at several locations of ductwork. Several tests were conducted to characterize the systems including the artificial holes introduced, parametric studies on the zone bag and evaluation of DPLT technique.

Test results indicate that when the static pressure inside the zone bag was higher than 0.30 psi, a proper seal is achieved. The local leakage estimations determined by DPLT were compared with the baseline. The technique produces relatively small scatter and bias; the mean difference is 0.05 % and the mean absolute difference is about 0.26 % of total air-handler flow. It can be inferred that the proposed technique estimates the local leakage accurately. The smoke tests confirmed the leak locations visually. Additional tests were performed to compare the total leakages determined by DPLT with the standard duct pressurization technique. The proposed technique determines the total leakage more accurately than duct pressurization test as the local leak pressures are considered. DPLT was able to identify the leak locations in ducts. Sealing the accessible leaks in registers SR1 and SR2 can reduce the total leakage by 3.7% for ADS I. Thus, by estimating the local duct leakage, the proposed technique offers two main advantages over duct pressurization technique: (i) identification of leak locations (ii) precise quantitative estimation of local and total leakage rates.

6.2. CFD Simulations

Six different leak geometries were simulated using CFD code. The aspect ratios of the leaks were varied between 1 and 3. The models were simulated at five different Reynolds numbers between 27000 and 83000.

The pressure loss coefficients were calculated for all the models. It was found that the pressure loss coefficient is a function of geometry in contrast to the regular formula which expresses it in terms of static pressure loss and mean velocity through the leak. The flow coefficient and pressure exponent were found for all leak geometries and at each Reynolds number using the power law model. Also, the leakages calculated by the CFD code and with the formula used to estimate duct leakage in mine ventilation were compared. Results indicate that using a simple correction factor of 0.5, can reduce the error in the empirical formula from 49% to 6%.

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