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Summary A residential ducted forced-air heating system was investigated to assess the impact of duct system leakage. Ductwork pressurisation and tracer gas techniques were used to quantify leakage in the heating duct system, and added infiltration to the house caused by duct leaks. Determination of leakage fraction by pressurisation tests showed a distribution loss of 23% in supply ductwork and 3% for the return duct during normal operation of the air heater's circulation fan. Tracer gas tests showed that the house infiltration is affected by the duct system leakage: infiltration increased from 0.1 ac h^{-1} for no ducting, to 0.21 and 0.5 ac h^{-1} with heating ductwork when the circulation fan is off and on respectively. A direct calculation shows the heat loss due to duct leakage to be about 45% of the house peak winter load. Hourly simulation of the space heating requirements indicates an annual increase of 35% in heating load due to heating duct leakage and transmission losses.

Domestic ducted forced-air heating: Duct system leakage and heating energy use

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List of symbols

DP	Duct pressure difference (Pa)
$Q_{s\&r}$	Total leakage flow for supply and return ducts ($m^3 s^{-1}$)
Q_{rr}	Return duct leakage flow ($m^3 s^{-1}$)
Q_{rs}	Supply ductwork leakage flow ($m^3 s^{-1}$)
$C(t_1)$	Initial concentration at time t_1
$C(t_2)$	Final concentration at time t_2
δt	$t_2 - t_1$ (min)
N_{av}	House average infiltration rate (ac h^{-1})
n_i	Infiltration rate for individual room (ac h^{-1})
V	Total volume of house (m^3)
v_i	Volume of individual room (m^3)
Q_{inf}	Total infiltration rate ($m^3 h^{-1}$)
Q_{nat}	Natural infiltration rate due to wind and stack effects ($m^3 h^{-1}$)
$Q_{balanced}$	Minimum of supply and return leakage ($m^3 h^{-1}$)
$Q_{unbalanced}$	Difference between supply and return leakage ($m^3 h^{-1}$).
E	Heat loss due to duct leakage (kW)
ΔV_{inf}	$= Q_{inf} - Q_{nat}$ ($m^3 s^{-1}$): Added infiltration to the house due to duct leakage when air heater fan is on.
T	Indoor temperature (°C)
T_o	Outside temperature (°C)
Q_{sl}	Supply ductwork leakage flow ($m^3 s^{-1}$)
T_s	Supply air temperature (°C)
Q_{rl}	Return duct leakage flow ($m^3 s^{-1}$)
T_{rt}	Return air temperature (°C)
T_{lt}	Loft air temperature (°C)
ρ	Density of air (kg m^{-3})
C_p	Specific heat capacity of air (kJ $kg^{-1} K^{-1}$)
E_{dt}	Duct transmission losses (W)
U	Overall thermal transmittance for supply ductwork (W $m^{-2} K^{-1}$)
A_s	Surface area of supply ducts (m^2)
ΔT_m	Logarithmic temperature difference

1 Introduction

Central ducted air heating and ventilation systems have been gaining widespread use in residential buildings in the UK as alternatives to the traditional wet central heating system. A ducted heating system with properly designed air distribution network, when installed in a building of good thermal envelope, would provide excellent indoor air quality and thermal comfort, and can eliminate the condensation which is a common problem in modern airtight houses.

The potential problems that could be identified with air systems are associated with air distribution duct losses and elevated infiltration rates in residences. Parker[1] has measured an average infiltration rate of 0.41 ac h^{-1} in homes with duct systems, and 0.24 ac h^{-1} for non–ducted homes. The elevated infiltration was found to have added about 28% to the heating load. In a study of nine single-family homes by Cunnings[2], an average infiltration rate of 0.62 ac h^{-1} was measured when the air distribution fan was running, and 0.22 ac h^{-1} when it was off. An increase of about 20% of the peak heating load was estimated when the distribution fan was operating 80% of the time during a typical winter season in Florida. In a test of thirty-one homes, Gammage[3] found an average increase of 80% in the infiltration rate due to air distribution fan operation. An average of about 10% increase in house leakiness was reported by Robinson[4] in a test of twenty homes by the fan pressurisation method. In all the above tests, the increase in infiltration rate was attributed to leaks in supply and return ducts which were located in unconditioned spaces.

The natural infiltration in a house with a ducted air heating system can be affected by the operation of the air distribution fan, when there is leakage in ductwork passing through unconditioned spaces. When the supply and return ducts pass through conditioned spaces, leaks in the ductwork can cause pressure and temperature imbalances between various zones, but the effect on infiltration of duct leakage is not severe. However, when the supply and return ducts pass through unconditioned spaces, leaks in the supply ducts will tend to cause the distribution fan to induce negative pressure and depressurise the house; whereas leaks in the return ducts will tend to cause the fan to induce positive pressure, causing pressurisation in the house. Consequently, the natural infiltration is affected by the supply and return ducts' leakage flow.

This investigation has been motivated by the increasing use of domestic ducted air heating systems in the UK, and the unavailability of any data showing the effect of duct system leakage on residential energy use. The objectives were:

(*a*) to measure leakage flow rate in supply and return ducts

(*b*) to measure infiltration due to duct leakage

(*c*) to measure house infiltration

(*d*) to assess the impact of duct leakage on ventilation

(*e*) to assess the impact of duct leakage on heating energy use.

2 Test house and heating system

The house selected for this study is an occupied three-bedroom bungalow. The original wet central heating system in the house was removed and a ducted air heating and ventilation heat recovery system was retrofitted. The building envelope construction consists of: external cavity wall filled with polystyrene bead and an outer leaf of thermalite block; a suspended timber floor with airbricks provided around the external wall to ventilate the crawlspace; a tiled roof with 150 mm thick loft insulation on a plasterboard ceiling; and double-glazed windows. The bungalow is situated in a confined compound in the city of Bath (England), and the degree of exposure of the site is below average. The house net floor area is 169 m^2 and its volume is 404 m^3. The floor plan with the ducted heating system layout is shown in Figure 1.

The ducted heating system consists of a 14.65 kW natural gas fired central air heater located in the utility room. The air heater has a circulation fan, a top return plenum connected to a return duct, and a bottom supply plenum connected to the main supply duct. Supply air from the heater is distributed to the rooms through a network of supply ducts with 19 mm thick sprayed foam insulation. All the supply ductwork is located in the ventilated crawlspace, and the supply air is delivered to the rooms via floor grilles. Return air from the rooms flows into the corridor through two transfer grilles located in the wall above the doors of the two large rooms, and slots provided above the doors of the small rooms. The air is returned to the heater via a ceiling return grille in the corridor and a return duct located in the loft. The return duct is joined by the outside air supply duct of the ventilation heat recovery unit before the return duct is connected to the air heater's return plenum.

The ventilation heat recovery (VHR) unit is located in the loft. It has four duct connections for: outside air intake and supply ducts, an extract duct carrying a mixture of extract air and flue gas, and an exhaust duct carrying the mixture of extract air and flue gas to the chimney. The unit has a supply fan and an extract fan. The supply fan supplies outside air through the heat exchanger into the return duct where it mixes with the return air. The extract fan extracts air from the bathrooms, toilet and kitchen through the extract duct system, and the flue gas from the heater, and discharges the mixture via the heat exchanger up the chimney.

3 Test procedures

3.1 Ductwork pressurisation method

Duct pressurisation is a standard way of measuring the leakage flow versus pressure difference characteristics of a duct system. The main benefit is that the duct leakage flows can be measured directly.

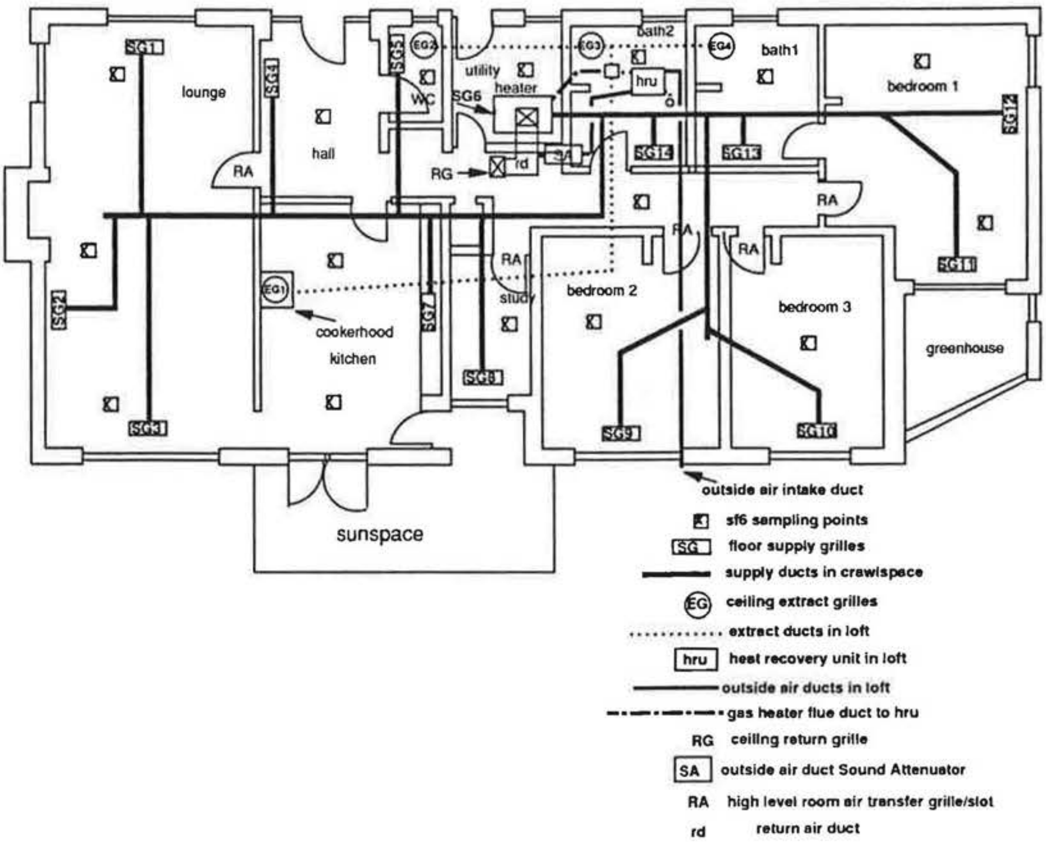

Figure 1 Floor plan and ducted heating system layout

Before the test, all the supply and return grilles were removed from the heating duct system, and the duct openings were tightly sealed using polyurethane foam and duct tape. The VHR unit was isolated from the heating ductwork by disconnecting the outside air supply duct of the VHR unit from the return duct. The flue gas duct was left connected to the air heater; however the other end where it joined the extract duct system before the VHR unit was isolated and sealed off. The VHR unit and the extract duct system were completely isolated from the heating ductwork.

In this study the leakage split between the supply and return sides of the heating duct system was determined. This split is required for the analysis of duct system leakage. A separate test fan was connected to the heating ductwork, and the pressurisation test was carried out firstly with the air heater connected to the ductwork and at a later date with the air heater removed from the ductwork due to concern about complete airtightness of the air heater in the first test.

At the beginning of the first test, the air heater was tested for leaks while still connected to the ductwork, along with the flue gas duct which had been sealed at the VHR unit end. The test fan was operated at about 60 Pa duct pressure difference. Duct tape was used to seal the heater where it was found to be leaking. The leakage flow for the combined supply and return ductwork was then measured by pressurisation between 3 and 35 Pa duct pressure difference. Afterwards, the return duct was sealed at the heater's return plenum with a slab of polyuretane foam and duct tape, to isolate the return duct from the supply ductwork. The leakage flow for the return duct alone was then measured by pressurisation, and for comparison by depressurisation, since the return duct normally operates under negative pressure. No difference was found between the return duct's pressurisation and depressurisation leakage flow measurements. The supply ductwork leakage flow was found by the difference between the measurements for the combined ductwork and the return duct only.

The pressurisation test was repeated at a later date to check whether the leakage flow measured in the above test was affected by the presence of the heater in the ductwork. The heater was removed from the heating duct system and the supply ductwork was leak tested independently of the return duct. A maximum variation of 5.5% leakage flow was found between the tests with and without the air heater.

In the above tests, air flow through the test fan is due to leaks in the ducts. The tracer gas constant injection rate technique was used to measure the air flow rate, and the duct pressure difference was measured in the main supply duct with an inclined manometer. SF_6 tracer gas was release from a compressed gas cylinder fitted with a needle valve regulator via a calibrated rotameter. The gas was injected upstream of the test fan into a 200 mm diameter duct connected to the fan, and air samples were collected at about 3 m downstream of the test fan to ensure good mixing of air and SF_6. The air samples were collected through a sample line connected via a multiport valve to a Bruel & Kjaer type 1302 gas analyser for concentration measurement. The background concentration in the loft where the measurement took place was also monitored. The range of concentration obtained during the measurements are as follows: 27 parts per million (ppm) at 5 Pa duct pressure to 95ppm at 26 Pa duct pressure, for the combined ductwork pressurisation; 146 ppm at 3 Pa to 40 ppm at 30 Pa, for the return duct pressurisation; 153 ppm at 3 Pa to 42 ppm at 30 Pa, for the return duct depressurisation; and from 7 parts per billion to 6.7 ppm for the background concentration in the loft.

3.2 *Tracer gas method*

Tracer gas testing was used to determine the heating duct system leakage, by measuring the house infiltration rate when all the heating ductwork terminals were open to the house, and when they were tightly sealed from the house.

Before the test the VHR unit was switched off the extract duct system was isolated from the house by sealing the extract terminals in the bathrooms, toilet and kitchen, with plastic sheet and duct tape. All the extract ducts were disconnected and sealed at the VHR unit end. The flue gas duct was left connected to the air heater, but was sealed at the VHR unit end where it joined the extract duct system, and the outside air intake and supply ducts of the VHR unit were disconnected and sealed. The house and the heating duct system were completely isolated and sealed from the extract duct system, the VHR unit and all outside connections.

Through isolating the house and heating duct system as described above, the heating ductwork formed part of the building envelope, and was at the same pressure as the interior of the house. Therefore any air flow into or from the house would have to be either through leaks in the building envelope only, when the heating ductwork is sealed from the house or through leaks in the building envelope and the heating duct system, when the ductwork is open to the house. The difference between the two infiltration measurements is due to duct leakage.

However, there are uncertainties in this method of measurement associated with the determination of a small flow by the difference between two large flow rates, and variability due to weather. The variations in both the inside and outside temperatures were known throughout the test from continuous monitoring in the house; however, the wind speed was measured only at the beginning and at the end of the test, and the wind direction was not measured. During the test period, the inside temperature varied between 17 and 18°C, while the external temperature varied between 12.5 and 16°C. Average wind speeds of about 0.32 m s^{-1} and 0.26 m s^{-1} were measured at the start and at the end of the test respectively. The test was conducted on a calm mild day, and the effect of fluctuation in wind speed and direction is expected to be minimal in the one-storey building.

Before the two tests described below the VHR unit, the extract duct system, the flue gas duct and all external connections were completely isolated and sealed from the house and the heating duct system. All windows, external doors and vents were closed, and all internal doors were left wide open. The burner of the air heater was turned off.

In the first test, the heating duct system was open to the house. The heater's circulation fan was left running. To open the heating ductwork to the house without any resistance to air flow, all the supply and return grilles were removed from the heating duct system, and, using the circulation fan, SF_6 was distributed into the space through the heating duct system by releasing the gas into the ductwork at upstream of the fan. SF_6 injection was stopped when the concentration in the space was about 25 ppm. The circulation fan was left to run for about five minutes after the injection had stopped to obtain good mixing of air in the house. The decay of SF_6 concentration in the house was monitored for about four hours at the sampling points shown in Figure 1.

In the second test, the heating duct system was sealed from the house. At the end of concentration decay measurement in the first test, the openings of all the supply and return ducts were sealed tightly using polyurethane foam and duct tape. More SF_6 was released directly from its cylinder into the space, and a portable fan was operated in each room in turn to mix the air thoroughly until the concentration was uniform at about 50 ppm in all rooms. Concentration decay was monitored at the sampling points in the house for about four hours.

In both tests tracer gas concentration was measured sequentially every 16 min at the sampling points shown in Figure 1, using the multiport valve shown in Figure 2.

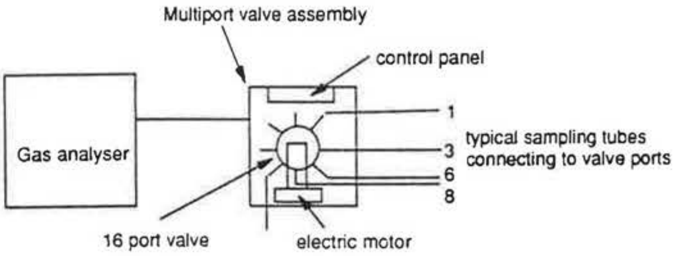

Figure 2 Tracer gas concentration measurement system

4 Test results

The heating duct system leakage was estimated by two methods: (*a*) leakage flow rate measurement at different duct pressure differences by ductwork pressurisation and (*b*) house infiltration measurement by tracer gas with heating ductwork sealed and open to the house.

4.1 Leakage split between supply and return ducts

The pressurisation method was used to determine the leakage split between the supply and return sides of the heating duct system. Measurement of the split by tracer gas methods was not attempted because of flow uncertainty associated with subtraction of two relatively large flow rates; there is only one return duct with a terminal located in the ceiling of the hall.

Regression analysis of the pressurisation test results yields the following

leakage flow equations, for the combined supply and return ductwork, the return duct only, and the supply ducts network respectively:

$$Q_{s\&r} = 0.0184\,\Delta P^{0.49} \qquad (1)$$

The standard deviation of this equation was 0.2652 for a correlation coefficient of 99.8%.

$$Q_r = 0.00162\,\Delta P^{0.665} \qquad (2)$$

The standard deviation of this equation was 0.3549 for a correlation coefficient of 92.4%.

$$Q_s = 0.0171\,\Delta P^{0.483} \qquad (3)$$

The standard deviation of this equation was 0.2987 for a correlation coefficient of 99.3%.

The above equations are valid for: $5 \leq \Delta P \leq 30$.

Figure 3 shows the plot of the pressurisation test data and the fitted equations. The variation of pressure along the supply ducts network and its effect on the leakage flow, under a given main supply duct pressure, is expected to be approximately the same for the pressurisation test and during normal system operation, as long as the driving pressure is the same. Therefore the leakage rate at any duct pressure during normal system operation can be determined from the above equations. Table 1 gives typical duct pressure differences measured during heating system operation, and the corresponding supply and return leakage split.

4.2 House and duct system infiltration

The house infiltration rate was measured by tracer gas concentration decay. The logarithm of concentration monitored

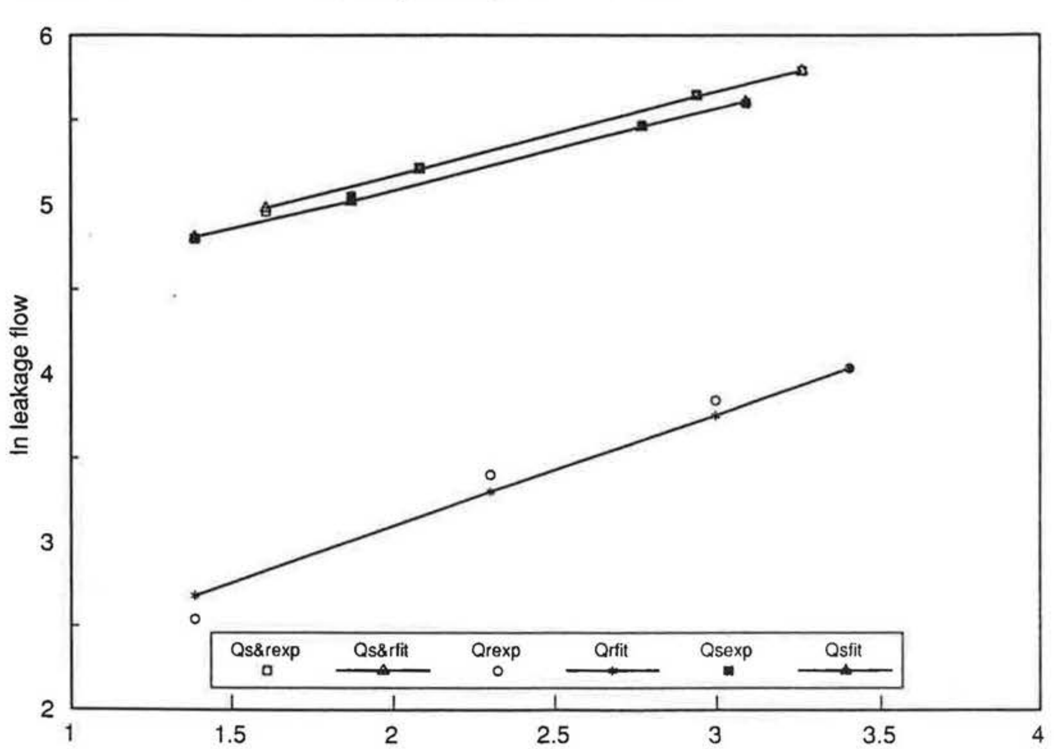

Figure 3 Logarithmic plot of leakage flow rate and duct pressure

Table 1 Duct pressure and leakage split during normal fan operation

Measurement location	Duct pressure (Pa)	Leakage flow ($m^3 h^{-1}$)
Main supply duct	10.5	195.84
Return mid-duct before fresh/return air mixing point	5	27.72
Return duct after mixing point	12	

in individual rooms in thehouse was plotted against time. The slope of the concentration decay curve

gives the infiltration rate for that location. Figure 4 shows a typical plot of logarithmic concentration decay rate data obtained from the two tests for various rooms and equation 4 gives the infiltration rate as obtained from the curve gradient. The house average infiltration was calculated using equation 5.

$$n_i = 60[\log_e C(t_1) - \log_e C(t_2)]/\delta t \quad (4)$$

$$N_{av} = \sum v_i n_i / V \quad (5)$$

4.3 Effect of duct leakage under air heater fan operation

Table 2 shows that the effect of duct leakage on infiltration is quite significant and greater than that of building envelope leakage. This effect is much greater during normal operation of the air heater's circulation fan due to unbalanced leakage. This occurs when there are larger pressure differentials driving the flow through the duct leaks than the ASHRAE[5] 4 Pa reference pressure driving air through building envelope leaks as a result of wind and stack effects. The average infiltration rate for the house with the heater circulation fan off was 0.1 ac h^{-1} without the heating duct system, and 0.21 ac h^{-1} with the heating ductwork. During normal operation of the circulation fan the house infiltration rate was estimated at about 0.5 ac h^{-1} using the following equation due to Feustel[6]:

$$Q_{inf} = (Q^2_{nat} + Q^2_{unbalanced})^{1/2} + Q_{balanced} \quad (4)$$

The naturally induced infiltration rate Q_{nat} is the product of house volume (404 m3) and the average natural infiltration rate (0.1 ac h^{-1}). Q_{inf} represents the total of natural infiltration and the added infiltration due to duct leakage when the air heater fan is on, and was estimated at 200.3 $m^3 h^{-1}$ (0.495 ac h^{-1}). $Q_{balanced}$ and $Q_{unbalanced}$ were estimated at 27.72 and 168.12 $m^3 h^{-1}$ respectively, using the supply and return leakage flows in Table 1. A ratio of 5.26 between Q_{inf} and Q_{nat} indicates that, during normal operation of the circulation fan of the air heater, the house infiltration rate had increased about five times due to duct leakage.

Table 2 House infiltration and heat loss (The extract duct system, VHR unit, outside air ducts and all external connections were isolated and sealed from house and heating ductwork during tests.)

	House infiltration (ac h^{-1})		
	Without heating ducts, test 1.	With heating ducts and heater fan off, test 2.	With heating ducts and heater fan on, by equation 6.
	0.1	0.21	0.495
Heat loss (kW)	8.18	8.54	9.49

4.4 Effect of duct leakage on heating load and energy use

The impact of duct system leakage and heat losses on heating load and energy consumption was determined by hourly simulation. The simulation was carried out for a heating season (22 September to 30 April) using the APACHE thermal model with weather data for Kew (England). The simulation takes into account the building dynamics, occupancy and operational characteristics of the air heating system.

The heating plant was simulated for the following cases: (*a*) the ideal case, when there is no duct leakage and all the supply ductwork is insulated with a minimum insulation thickness of 50 mm; (*b*) when there is duct leakage and all the supply ductwork has a minimum of 50 mm insulation thickness, to estimate the impact of duct system leakage only; (*c*) when there is no duct leakage and all the supply ductwork is as installed with 19 mm insulation thickness, to estimate duct

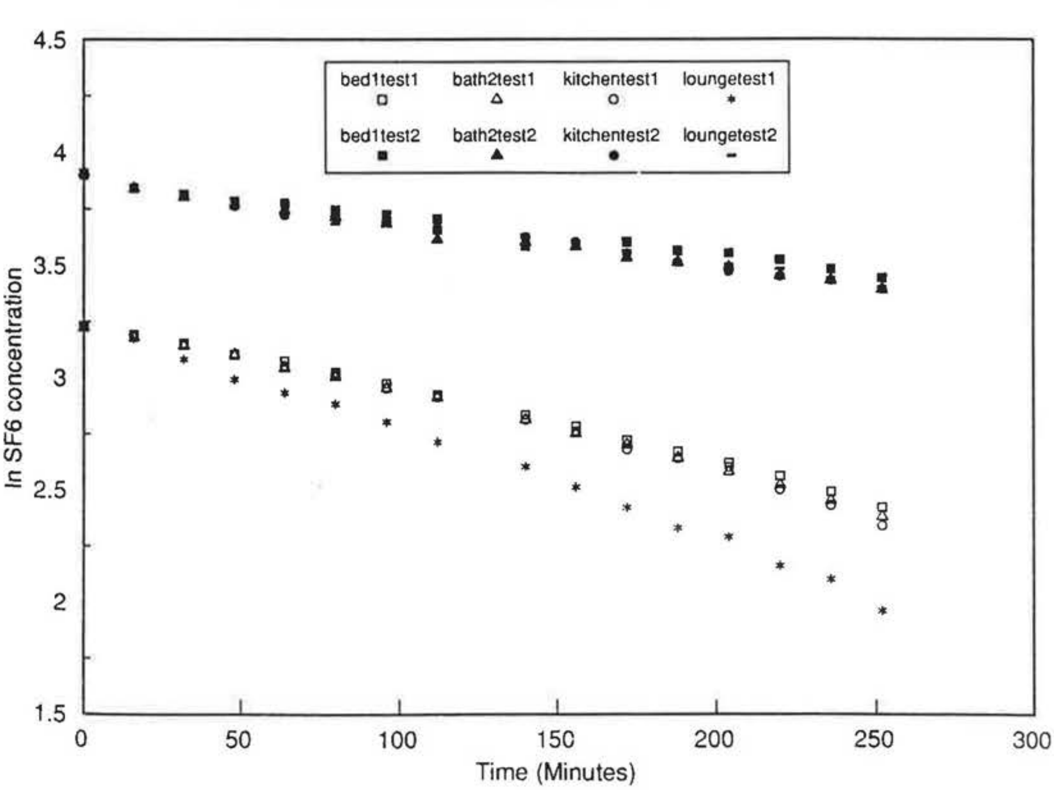

Figure 4 Typical logarithmic plot of concentration decay

heat losses only due to inadequate insulation; (*d*) the real situation with duct leakage and inadequate 19 mm thick supply ductwork insulation. The complete air system flow circuit as modelled for case (*d*) is shown in Figure 5. Since the crawlspace contains all the ductwork its average temperature would be elevated despite airbrick ventilation as a result of the losses from theductwork. To take this into account the crawlspace average temperature has been increased by 2 K. Otherwise all the supply duct leakage and heat losses were considered as dead losses in the simulation.

house over the period 22 September–30 April was estimated at 15 205 kWh.

As an alternative analysis to the hourly simulation, the increase in heating load due to duct leakage and duct heat losses at any instant can be calculated using equations 7 and 8. Equation 7 shows that the heat loss due to duct leakage is made up of three elements: (i) added infiltration; (ii) dead loss of supply air; (iii) loft air entering the return duct.

$$E_{dl} = \Delta V_{inf}(T_r - T_o)\rho C_p + Q_{sl}(T_s - T_r)\rho C_p - Q_{rl}(T_{rt} - T_{lt})\rho C_p \quad (7)$$

$$E_{dt} = UA_s \Delta T_m \quad (8)$$

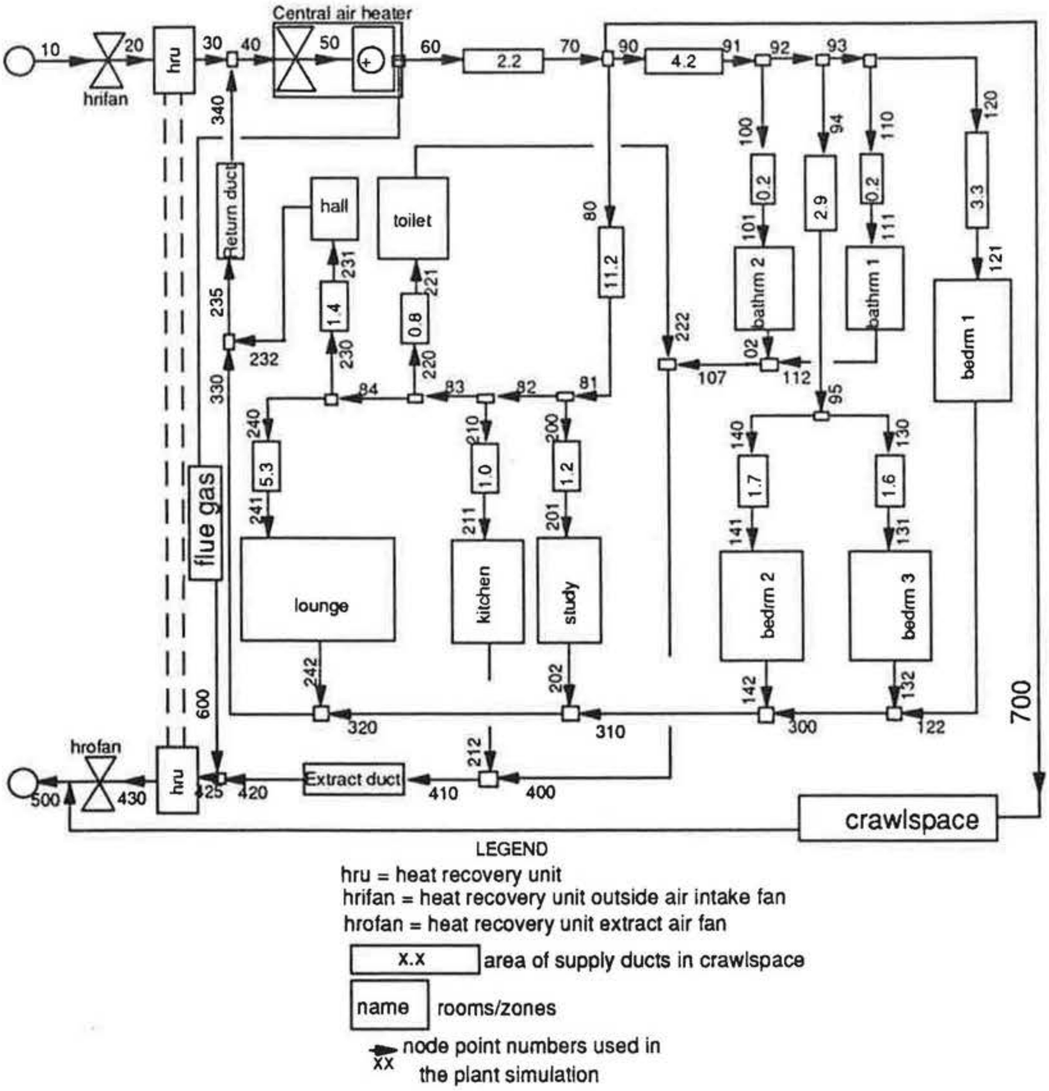

Figure 5 Air system circuit used in the heating plant dynamic simulation

The simulation results show the building's annual heating load to be 8464 kWh for the ideal case without duct system losses, and 12 950 kWh for the real situation with duct system losses. The increase in annual heating load due to duct leakage was estimated at 2610 kWh, and due to duct heat losses at 1876 kWh. This meant that annual heating load is increased by about 53% due to the duct system losses. In other words, 35% of the annual heating output of the installed heating system is lost through duct system losses. Using the predicted 12 950kWh annual heating load and a 75% seasonal efficiency for the natural gas fired air heater, the annual heating energy use for the bungalow was estimated at 17 267 kWh. Based on the actual gas consumption, shown in Figure 6, and calorific values from the gas bills, the real space heating energy use the

The heat losses due to duct system leakage and duct transmission losses were estimated at 3.7 and 3.06 kW respectively, using the following temperatures recorded during the test with equations 7 and 8: 18°C indoor, 9°C outside, 68°C supply air, 17°C return air, 11°C loft air, 12°C crawlspace, and an estimated U-value of 1.49 W $m^{-2}K^{-1}$ for the supply ductwork with 19mm of sprayed foam insulation. At the peak winter condition the temperatures were: –5°C outside, 18°C indoors, –2°C loft, 0°C crawlspace, 18°C return air, and 68°C supply air. The heat losses were 3.7 kW due to duct transmission losses, and 4.3kW or about 45% of the house peak winter heat load due to duct leakage.

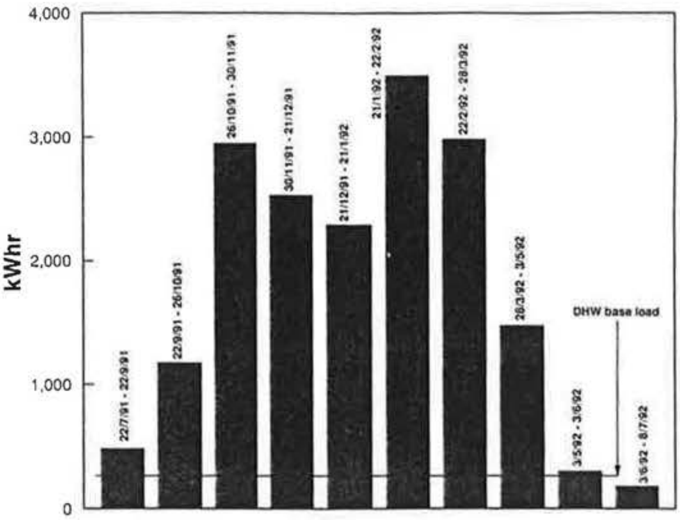

Figure 6 Recorded gas consumption

5 Conclusion

The results of the investigation have shown that duct system leakage, when the heating ductwork is located in unconditioned spaces, has a large impact on heating energy use and comfort conditions. The duct pressurisation and tracer gas tests have proved very useful in identifying and quantifying the duct system leakage.

Determination of the leakage fraction shows a distribution loss of 3% in the return duct and 23% in the supply ductwork. The duct system leakage rate is found to be about seven times the leakage limit stipulated for low-pressure velocity (Class A) sheet metal ductwork accoding to *DW142*[7]. The single return duct is accessible in the loft, while all the supply ductwork is in the crawlspace. The supply duct leakage is due to poor ductwork construction attributable to a considerable lack care and planning by the duct installer to ensure airtightness in a difficult installation. It was discovered that the supply duct network was constructed in the crawlspace by removing few floorboards and pushing pieces of pre-insulated duct end-to-end with no attempt to seal the joints between the duct pieces. In view of the magnitude of the leakage problem in this study, we recommend that when air distribution ducts are to be located in such an inaccessible space the design engineer, who must be aware of the installation difficulties at the design stage, should provide installation recommendations and adequate site supervision and quality control during installation. Had this been done in the present case the duct leakage problem could have been eliminated or at least minimised. Unfortunately, because of the inaccessibility of the supply ductwork, remedial work is not straightforward and has not been undertaken in the system used for the present study.

The results obtained from the duct leakage and infiltration measurements indicate that when heating ductwork is located in unconditioned spaces house infiltration can be affected if the ducts leak. Infiltration in the bungalow increased from 0.1 ac h^{-1} without the heating duct system to 0.21 ac h^{-1} with the duct system when the air heater fan is off and 0.5 ac h^{-1} when the fan is on. The infiltration at 0.5 ac h^{-1} due to duct leakage during normal operation of the air heater fan unwanted, since the VHR unit provides the required quantity of fresh air to the house. The duct leaks have therefore spoiled the low infiltration rate which is essential to obtain the full benefit of the VHR system in an otherwise airtight house.

Analyses show that the increase in heat loss due to duct leakage is about 45% of the house heat load at peak winter condition. By hourly simulation, the heating duct system leakage is estimated to cause a 2610kWh y^{-1} increase in annual heating load.

The test result for this bungalow, which has been retrofitted with a ducted air heating system following the removal of the original wet central heating system, should not be taken as a broad representation of installed ducted air heating systems in UK housing. However, the result indicates that the effect of duct system leakage on heating energy consumption could be very large. Therefore a more robust research effort is recommended to ascertain the extent and impact of duct leakage in new and old housing stock in the UK, especially when the air distribution ducts pass through unconditioned spaces. The research may lead to the development of measurement and performance standards for domestic building ductwork.

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