VENTILATION AND HEAT RECOVERY IN SUPERINSULATED HOUSES

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ABSTRACT

With the gradual reduction in background air infiltration in houses a dependable method of maintaining air quality is required. Mechanical ventilation with heat recovery supplies a guaranteed amount of fresh air and reduces the associated energy penalties. The basis for selecting a ventilation system for a group of superinsulated houses is discussed with particular reference to the practical issues of installation and maintenance. The layout of the chosen system is explained in detail and problems encountered are highlighted. Results are presented from intensively monitoring one of the ventilation systems installed. The temperature efficiency of the heat exchanger is shown to be in the range 70-80% and the coefficient of performance is always greater than 3. At a CoP of 2.5 and above the system is more cost-effective than introducing the same volume of air and heating it by gas at boiler efficiency of 75%.

INTRODUCTION

In the past houses have been ventilated more by accident than design. Air may enter through numerous cracks and holes in the fabric of the building, at the whim of the prevailing meteorological conditions. Whilst passive ventilation systems have been shown to work satisfactorily[1], their performance can not be guaranteed and weather conditions may conspire against them. In addition it often proves necessary to install some form of mechanical extract in areas of high humidity such as kitchens and bathrooms.

Mechanical ventilation introduces a controlled amount fresh air into a house and an air to air heat exchanger reduces the energy lost by this process. In very well sealed low energy houses with air change rates below 0.2 per hour mechanical ventilation is an almost inevitable choice.

Several benefits derive from the installation of a mechanical ventilation system. The first has already been mentioned, namely controllability. The filtering of 90% of the air entering the house reduces the ingress of contaminants. If the system is correctly designed and installed, all rooms within the house will be ventilated, leaving no stagnant areas where condensation or mould growth might occur.

This paper discusses the installation of a mechanical ventilation system with heat recovery in a group of superinsulated houses in Milton Keynes. The houses have been monitored since January 1986 by the Research in Building group at the Polytechnic of Central London with funding from the Commission of the European Communities. Particular reference will be made to the main demonstration house which is intensively monitored. Several air infiltration experiments have been carried out in this house revealing a background air change rate between 0.1 and 0.2 per hour.[2]

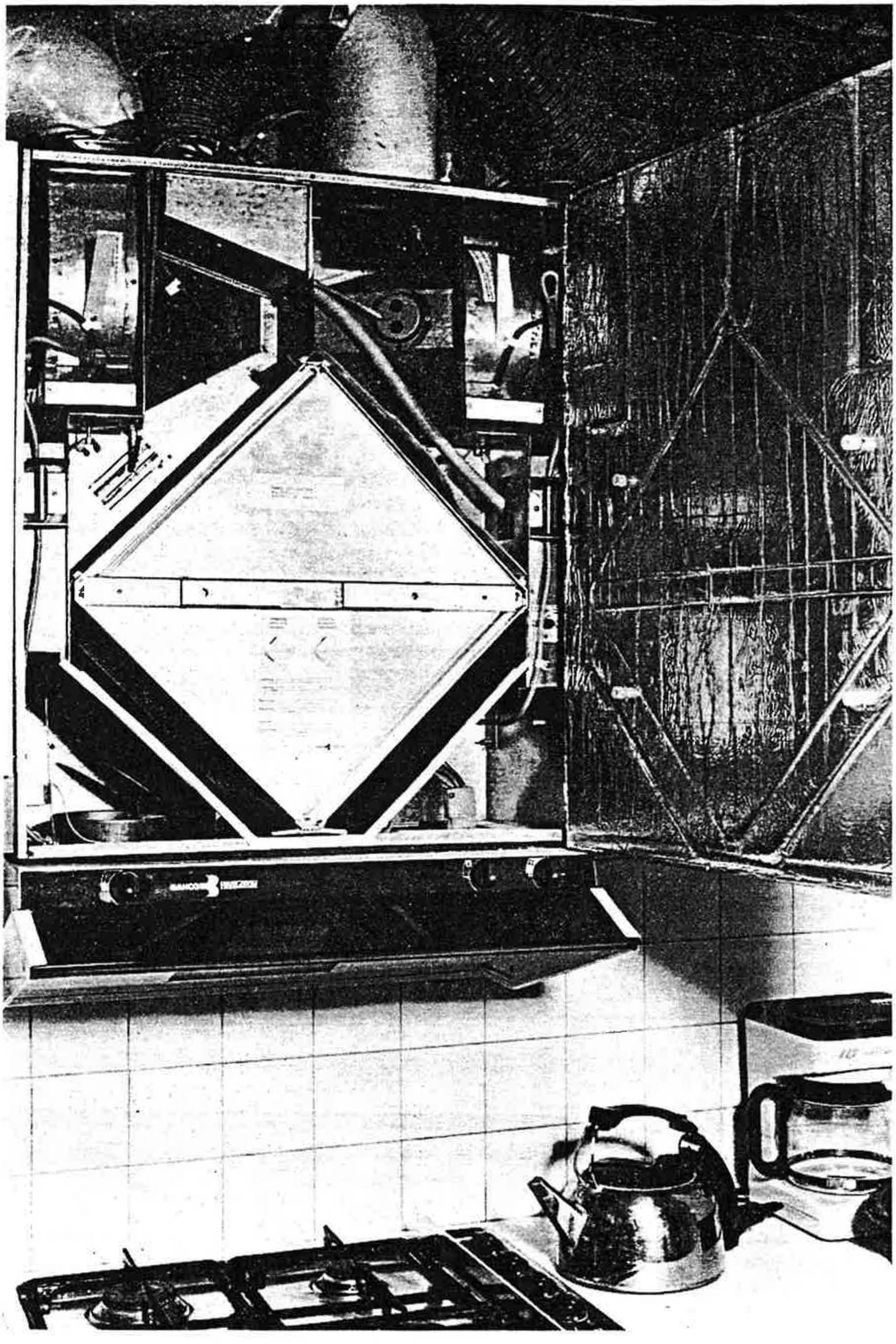

Figure 1 BAHCO Ventilation Unit Installed In Demonstration House Kitchen

SPECIFICATION CRITERIA

When specifying the mechanical ventilation system for the superinsulated houses in Milton Keynes a number of requirements were established. The following list is by no means exhaustive, but sets out the pertinent issues in this instance.

Capital and Running Costs

The capital cost generally dictates whether or not a system is installed at all, rather than which system is installed. In most cases it would be difficult to justify the total capital expenditure on the basis of the auxiliary energy saved by the heat exchanger. When assessing the system for the superinsulated houses the capital cost was discounted by the reduced specification heating system and the savings on other ventilation devices that would have been required. The auxiliary energy saved by the heat exchanger should more than offset the running costs of the system, and possibly even the maintenance costs.

Maintenance

Maintenance costs can be greatly influenced by accessibility. The location of the major system components in one unit above the cooker hood in the kitchen was the main reason for choosing the BAHCO ventilation system for the superinsulated houses. This unit allows regular maintenance like changing filters and cleaning heat exchangers to be performed simply by the occupant. However, if the unit were located in the loft space, the house owner may not wish to, or be able to perform the regular maintenance, and would have to employ someone to carry out the work. Furthermore, the less accessible the unit, the less likely that regular maintenance will be undertaken at all, and this may lead to serious faults with the system which could be expensive to repair.

Efficiency

The efficiency of the heat exchanger will depend largely upon type. The commonly available types of heat exchanger are set out briefly in Table 1.

Table 1 Common Heat Exchanger Types

1	Run around coil	Heat exchanger coils are located in exhaust and intake air streams. A heat exchanger fluid is pumped between the coils. Efficiencies* are up to 50% and the system is mainly used in industry.
2	Rotating regenerator	The regenerator wheel spans adjacent intake and exhaust ducts. Spinning slowly the wheel picks up heat in one and transfers it to the other. Efficiency is high. Only occasionally found in domestic use.
3	Plate regenerator	A change over valve is intermittently operated to pass both intake and exhaust air flows, in turn, over two sets of absorber plates. Very high efficiencies are possible. Examples of domestic units exist.
4	Plate heat exchanger	The two air flows pass through adjacent gaps between thin metal plates in a cross flow pattern. Heat is exchanged across the plates. Efficiency up to 75%. This is most common domestic heat exchanger.

* Temperature efficiency defined in later section

The system chosen for the superinsulated houses, shown in Figure 1, was manufactured by BAHCO of Sweden, and uses an aluminium cross flow heat exchanger.

Quality of Components

The quality of the components will be largely reflected in the price differential between systems. The air distribution system will often be built into the fabric of the building and should, therefore, be capable of lasting for the lifetime of the building. The same should be true for the casings of the major components. Components such as fans will eventually require repair or replacement, and here again accessibility will reduce maintenance costs. As most systems incorporate a cooker hood extract the performance in the event of a fire is important. The BAHCO ventilation system has number of safety devices which will close fire dampers and shut off the fans in the event of a fire.

Operating Modes

It is desirable that the ventilation system provides of a variety of operating modes. Generally, these modes will generally be produced by varying the fan speed. The BAHCO unit installed in the superinsulated houses provides five distinct modes and off. These modes are set out in Table 2.

Table 2 BAHCO Operating Modes

1 Low	During very cold weather or periods of non-occupation.
2 Normal	Everyday operation.
3 Boost* - cooking	Extract rate increased through cooker hood only.
4 High humidity*	Extract and supply rate increased throughout house.
5 Summer	Any fan speed and extract by-passes heat exchanger.

* Boost and high humidity are considered equal for the purposes of analysis.

Condensation and Frosting the Heat Exchanger

Air extracted from the house will be warm and most likely moist. When this air comes into contact with the cold exchanger or regenerator plates condensation may occur. The heat exchanger or regenerator plates must, therefore, be resistant to corrosion, and an safe exit for the condensate must be provided. Condensation is a possibility in all types of heat exchanger. When it occurs the latent heat released serves to improve the performance of the heat exchanger. The BAHCO system installed in the superinsulated houses has an aluminium heat exchanger and drains the condensate through a trapped seal to the household waste water system.

Frosting of the heat exchanger is less of a problem in the UK than in other countries. However many systems are designed to cope with this problem. The BAHCO unit has a temperature operated damper which closes off the fresh air intake for a period of time and allows the extract air to defrost the heat exchanger.

Air Filtering

It is advisable for air filtering to take place in all forms of heat exchanger. This avoid contamination in a change-over or wheel systems, and blockage of the air gaps in a plate heat exchanger. Ideally the air filtering devices should

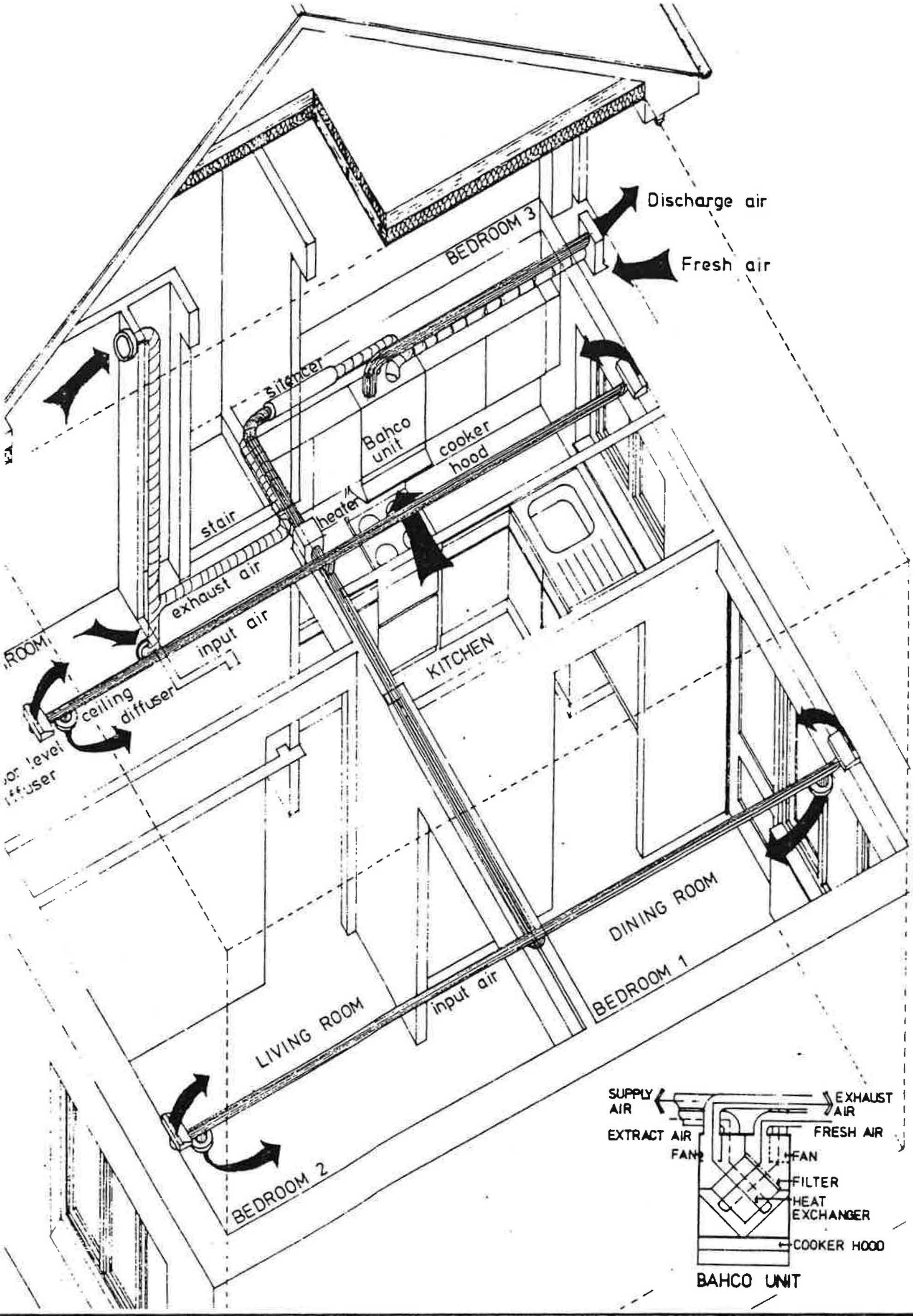

Figure 2 Ventilation System Layout

be easily accessible for cleaning, or replacement. In systems which employ a cooker hood extract, a grease filter should also be fitted. Again this filter should be accessible for cleaning.

Noise

The main source of noise in a heat exchanger is likely to be the fans. A degree of sound insulation is generally provided by the casing to the fans. In most systems the fan units should be supported upon resilient mountings, in order to avoid structure borne sound transmission. This is a particular problem with units mounted in the loft space above bedrooms. The siting of the BAHCO unit above the cooker hood in the kitchen has its advantages, as the very low noise level emitted rarely exceeds the background noise from other appliances.

System Balancing

Some form of air flow rate adjustment is desirable to avoid a large imbalance between the intake and exhaust air flow rates (the reasons for this are explained in a later section). It may also be desirable to balance the system such that, either a slightly positive, or negative, pressure is achieved in the house. Most systems have a means of balancing. Balancing the BAHCO system involves adjustment of the input and exhaust air registers to restrict the flow of air in each direction. This operation should be carried out in combination with instrumentation that can accurately measure the resulting air flow rate. Unfortunately such equipment is not readily available in the UK, and a "suck it and see" approach is more often adopted.

SYSTEM LAYOUT IN SUPERINSULATED HOUSES AT MILTON KEYNES

Figure 2 shows the ventilation duct distribution system in relation to the structure of a "left handed" superinsulated house (Figure 1 illustrates a BAHCO unit in a "right handed" house of a semi-detached pair). A schematic of the system is given in Figure 3.

Intake and Exhaust Ducts

The fresh air intake and stale air exhaust are combined in one unit on the external wall. The exhaust air exits above the intake. The buoyancy of the warmer exhaust air will keep the air streams separate, provided that there are no large objects near by causing turbulence. The intake and exhaust air ducts are insulated and enclosed within a vapour barrier from the external wall to the ventilation unit. This prevents warm moist air from the house condensing on the outside of the relatively cold ducts, as well as preventing extra heat loss by this route. The point at which both ducts pass through the wall structure is quite difficult to seal, being very close to the wall and ceiling. The solution eventually adopted to this problem was to inject expanding UF foam around the ducts from the outside into a boxed section of the timber frame.

Ventilation and Heat Exchange Unit

As illustrated in Figure 1 BAHCO unit contains two fans, an air filter, a heat exchanger and has the cooker hood unit attached underneath. The cooker hood unit houses a grease filter, light and all the electrical control circuitry. Although the unit is very compact, the depth conforms to continental kitchen unit sizes and is generally 100mm taller than standard British made units. This problem was resolved by adding a light baffle to the underside of the kitchen wall units in the superinsulated houses to make up the extra height.

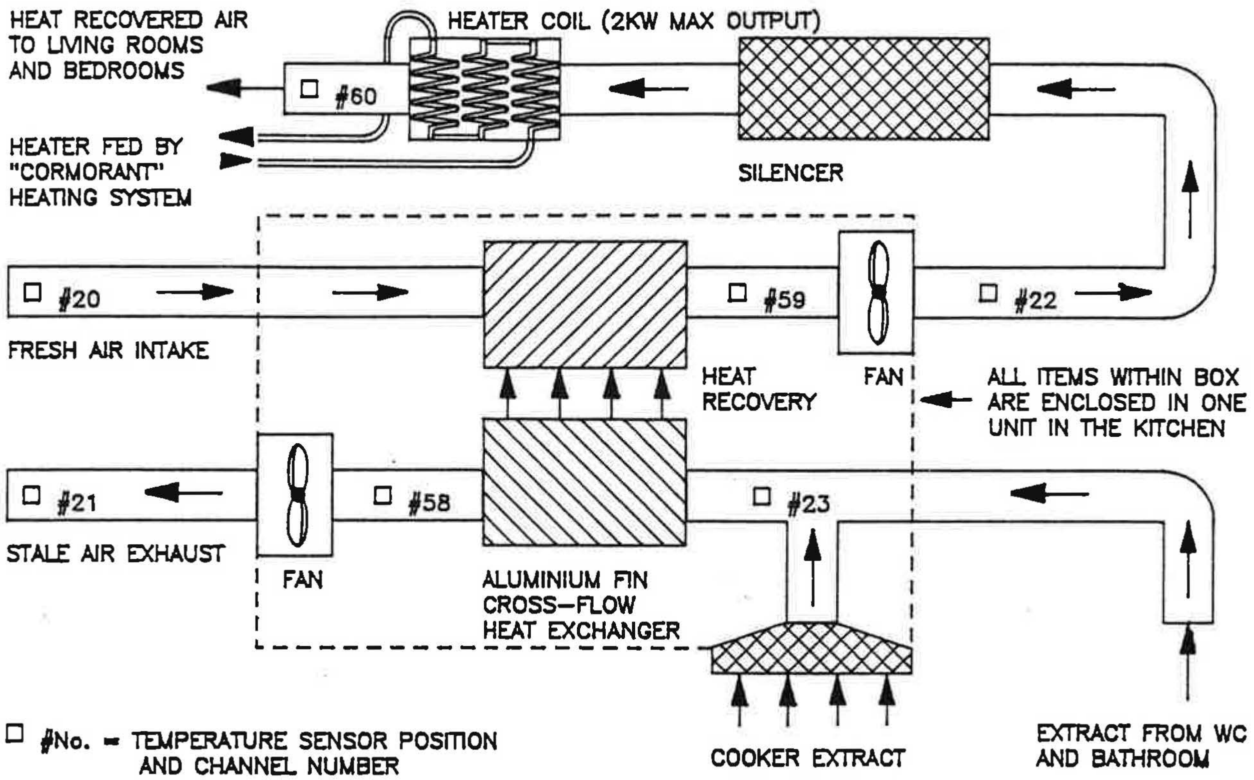

Figure 3 Ventilation System Schematic

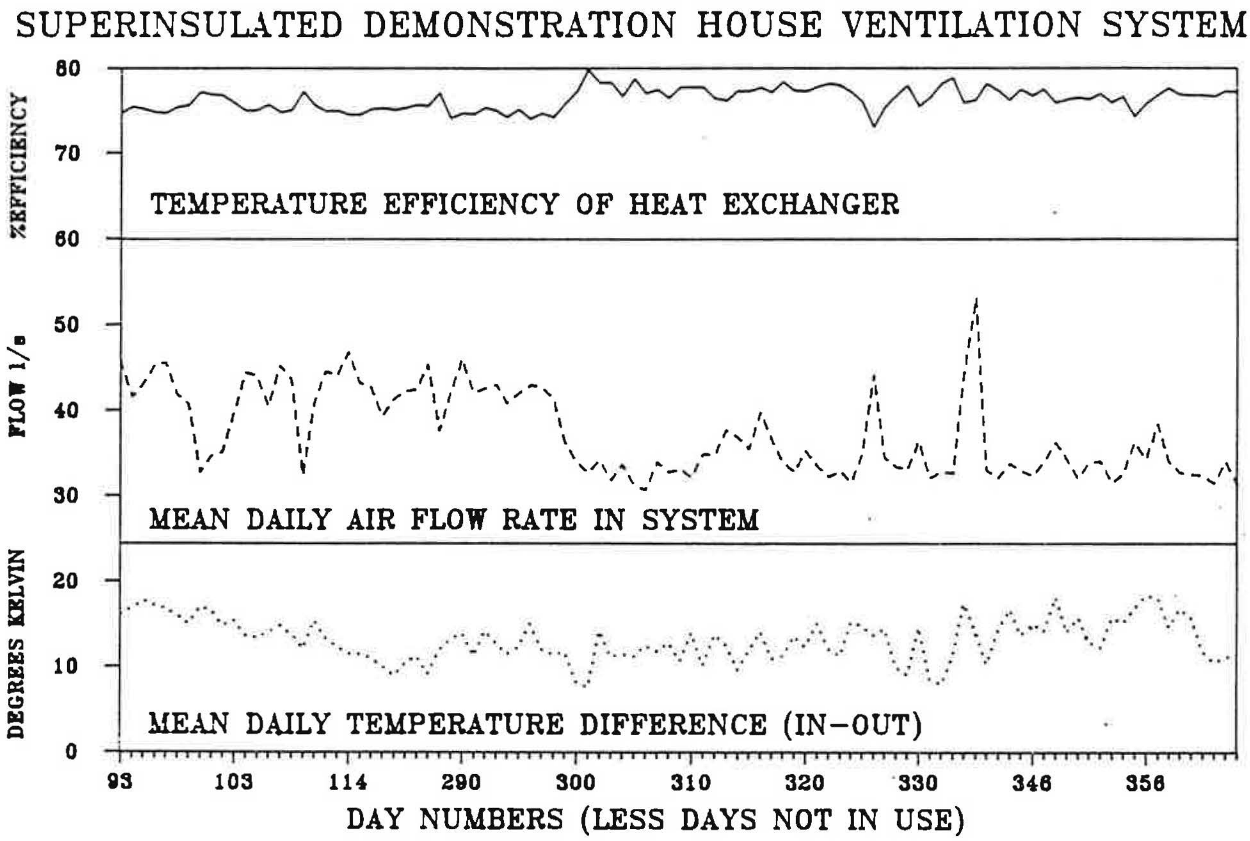

Figure 4 Temperature Efficiency of BAHCO Heat Excahnger

Integration with the Space Heating System

A small water to air heat exchanger coil is located in the supply air duct just after the silencer. The coil has a heat output rate of ~1.5kW with ventilation system in the normal mode and ~2kW when in the boost mode. The heater was sized to meet the design heat loss rate of the superinsulated house which is 1.5kW. Over-sizing was considered unnecessary as the ventilation rate is strictly controlled, and the house has a very long capacity to loss ratio (ie it does not cool down significantly over unheated periods). The Cormorant Space and Water Heating system which supplies the water to air heat exchanger coil is described in the paper "Experience of a Year Monitoring Four superinsulated Houses", also in these proceedings.

Air Extraction and Distribution System

The ducts installed in the superinsulated houses are the thin gauge metal, spiral wound type. This type of duct is more difficult to cut than the flexible plastic or concertina metal foil type, but it is far more resistant to damage. Another important feature of this duct type is the smooth internal surface which reduces the overall system resistance, as compared to profiled ducts, which tend to produce turbulence. Corners are negotiated with a range of fixed bends, which slot inside the straight ducts. The joints are sealed by means of a soft EPDM gasket. Duct tape may also be used to seal the outside of joints, and good adhesion is generally obtained onto the smooth surface.

Air is extracted from the house through the cooker hood in the kitchen and at high level in the bathroom and WC. Air is supplied to the living room, dining room, hall and bedrooms via ducts in the intermediate floor. The intermediate floor was chosen for distribution partly because of the economy of shorter duct runs, but mainly to avoid ducts puncturing the vapour barrier at the first floor ceiling level. It is important to introduce potentially cooler air at high level on the ground floor to allow mixing with the warmer air close to the ceiling. Introducing cooler air a low level in the bedrooms is not a problem due to the low flow rates and the usage pattern of the rooms.

In the supply system, one main duct travels perpendicular to the direction of the floor joists and is boxed into the main partition wall between the living and dining rooms. All the remaining ducts travel in the same direction as the floor joists within the depth of the floor.

PERFORMANCE MONITORING

Performance monitoring of the superinsulated house began in January 1986, but detailed monitoring of the ventilation system did not begin until a number of temperature sensors were installed and flow rates measured in April 1986.

Temperature Measurements in the Ventilation System

The positions of the temperature sensors in the ventilation system are shown in Figure 3. The temperature sensors used are AD590's, which give a standard current response to temperature and are extremely linear.

Ventilation Unit Power Consumption

A current clamp is used to monitor the current drawn by the BAHCO ventilation unit. This device, despite many calibration attempts, is not highly accurate, but is sufficiently repeatable to distinguish between the various operating modes. In order to establish the power consumption of the fans a ventilation unit was run for several days at a time in each mode and the electricity consumed was monitored with a calibrated watt meter. The power rating of each mode is as follows; low - 70W, normal - 95W, boost - 160W.

Air Flow Rate Measurements in the Ventilation System

The duct air flow speeds were measured on a relatively still day January when wind speeds did not exceed 3m/s. Air speed measurements were made using a hot wire anemometer with an accuracy of ±5%. Measurements were taken at the mid point of the first straight run of duct after the ventilation unit. Table 3 gives the volume flow rates derived from the results.

Table 3 shows a reduction in air flow rate over the heat exchanger unit for the input air stream and an increase for the extract air stream. The increase in flow rate in the extract air stream is exaggerated as the measurement was made in the duct from the bathroom and WC, which excludes the contribution from the cooker hood unit.

Table 3 Calculated Duct Air Flow Rates			Mean Flow Rate (l/s & m³/h)		
Duct name	Diameter	Units	Low	Normal	Boost
Fresh air intake	125mm	l/s m³/h	33 118	46 167	60 217
Stale air exhaust	125mm	l/s m³/h	35 127	48 173	72 258
Air supply to house	125mm	l/s m³/h	26 92	34 124	55 198
Air extract from house	100mm	l/s m³/h	19 68	26 95	36 130

THEORY OF HEAT EXCHANGER PERFORMANCE

There are many different ways to define the performance of a heat exchanger. However, the two most important factors to the house owner are the temperature of the air input to the house and the heat saved in relation to the electricity used. The former is described by the temperature efficiency and the later by the coefficient of performance.

Temperature Efficiency of the Heat Exchanger

The effectiveness of a heat exchanger (ϵ) is commonly defined to be[3]

$$\epsilon = \frac{\text{actual heat recovery}}{\text{maximum possible heat recovery}} = \frac{q}{q_{max}} \quad ....(1)$$

For most heat exchangers, these heat recoveries are evaluated simply in terms of the mass flow rates and the temperature differences for each fluid. In the case of an air to air heat exchanger this is sometimes true, but often condensation or even frosting may occur due water vapour in the warm moist extract air. Under these circumstances the simplified expression no longer represents the effectiveness of heat recovery, but is nevertheless represents the temperature efficiency (ϵ_T, or temperature effectiveness).

$$\epsilon_T = \frac{T_{c,o} - T_{c,i}}{T_{h,i} - T_{c,i}} = \frac{\text{temperature rise of input air}}{\text{maximum possible temperature rise}} \quad ....(2)$$

where

$_c$ represents the cold air flow,
$_h$ represents the hot or warm air flow,
$_o$ represents the condition at the heat exchanger outlet,
$_i$ represents the condition at the heat exchanger inlet.

Substituting the temperature channel numbers from the monitored BAHCO heat exchanger, as shown in Figure 3, into equation (2) we have

$$\epsilon_T = \frac{T_{\#59} - T_{\#20}}{T_{\#23} - T_{\#20}} = \frac{\text{temperature rise of input air}}{\text{maximum possible temperature rise}} \ldots.(3)$$

A flow imbalance in the input and exhaust air streams has been shown to improve the efficiency of the heat exchanger. However, in a house, unbalanced flows merely causes air leakage to occur elsewhere upon which no heat exchange is taking place. The net effect will be to lower the efficiency. To partially account for unbalanced air flows equation (3) can be multiplied by the capacity rate ratio R, where

$$R = \frac{v_{min} \cdot \rho C}{v_{max} \cdot \rho C} \ldots\ldots.(4)$$

where

v is the volume flow rate in m^3/h,
ρC is the volumetric specific heat of air at that temperature.

As can be seen from Table 3 the fresh air intake and stale air exhaust are reasonably well balanced in all modes, except boost. In the results presented here the capacity rate ratio R was only applied to the boost mode. As the ventilation system only operates for a small percentage of the time in this mode the mean operating temperature efficiency is not greatly affected.

<u>Coefficient of Performance of the Heat Exchanger</u>

The coefficient of performance of a heat pump or heat exchanger is defined as[4]

$$CoP \doteq \frac{Q_{out}}{w} \ldots\ldots..(5)$$

where, for a heat exchanger

$$Q_{out} = Q_{in} + Q_{rec} + w_u \ldots\ldots..(6)$$

where

Q_{out} is the heat output,
Q_{in} is the heat input,
Q_{rec} is the heat recovered from the extract air,
w is the total fan energy supplied,
w_u is the fan energy usefully transferred to the incoming air.

As can be seen from Figure 3, we may obtain Q_{out} directly from the temperature difference between sensor #20 in the fresh air intake and sensor #22 in the supply air duct after the heat exchanger and fan. Therefore, the coefficient of performance of the BAHCO heat exchanger installed in the demonstration superinsulated house is given as

$$CoP = \frac{v_{mean} \cdot (T_{\#22} - T_{\#20}) \cdot \rho C}{w} \ldots\ldots..(7)$$

where

v_{mean} is the mean of the input flow rate each side of the heat exchanger.

Using the mean of the input flow rates before and after the heat exchanger assumes that the flow rate is reduced by half the difference before and half after, or across, the heat exchanger (see Table 3 for the relevant flow rates).

PERFORMANCE ANALYSIS

The data collected from April. 1986 to December 1986 has been analysed using the theoretical principles set out in the previous section. The results presented relate mainly to the ventilation system in the demonstration house as this is the most intensively monitored. This house is occupied by a researcher from the Polytechnic of Central London and his family. However, it is stressed that no attempt has been made to "run" the system in this house to achieve optimal performance.

Usage and Operating Costs

Amongst the house owners there is a high level of satisfaction with the ventilation systems. Some appear to use the systems more discerningly than others, switching on only in cold weather and operating in the low mode for long periods. In all the superinsulated houses there is a complete absence of condensation. Several families have remarked upon how quickly misting disappeares after showering, and how venting a tumble drier directly into the house, in order to benefit from the waste heat, presents no problems at all.

The use of the ventilation system to distribute the heat from the water to air heat exchanger is not entirely successful. The heater coil is a large as it practically might be, but the system is often found to be lacking capacity. The only method available of increasing heat output is to boost the air flow rate. Even the flow rate of 45l/s in the boost mode is insufficient in some conditions. It is also largely self-defeating as the system merely introduces more cold air to the house. A partially re-circulatory system, or an entirely separate single point heater would possibly be better to suited to the task.

Table 4 gives details of operation of the ventilation systems in all four houses, together with the resulting costs. The total time in use varies from just under half the year in house 1 to just over three quarters of the year in house 2. The boost mode is typically used the least by all households, as might be expected. The majority of the time the systems are operated in the low or normal mode. Comparing the costs for house 0 (the demonstration house) with house 2, roughly £6 is saved by using off-peak electricity.

Table 4 BAHCO Usage and Cost	HOUSE 0	HOUSE 1	HOUSE 2	HOUSE 3
Hours in low mode	3301	2646	4219	298
Hours in normal mode	2704	414	2173	3330
Hours in boost mode	947	605	1053	534
Total hours operated in 1986	6953	3665	7445	4162
Off-peak electricity (kWh)	174	82	0	0
On-peak electricity (kWh)	464	239	670	423
Total electricity (kWh)	640	321	670	423
Cost of electricity for 1986	£28.65	£14.58	£36.52	£23.05

Temperature Efficiency

Figure 4 shows the mean daily temperature efficiency for the BAHCO heat exchanger in the superinsulated demonstration house. Only those days when the system operation exceeded 23 hours are included. Also plotted on the same graph are the mean daily temperature differences from inside to outside and the mean daily air flow rate through the heat exchanger. One can immediately see

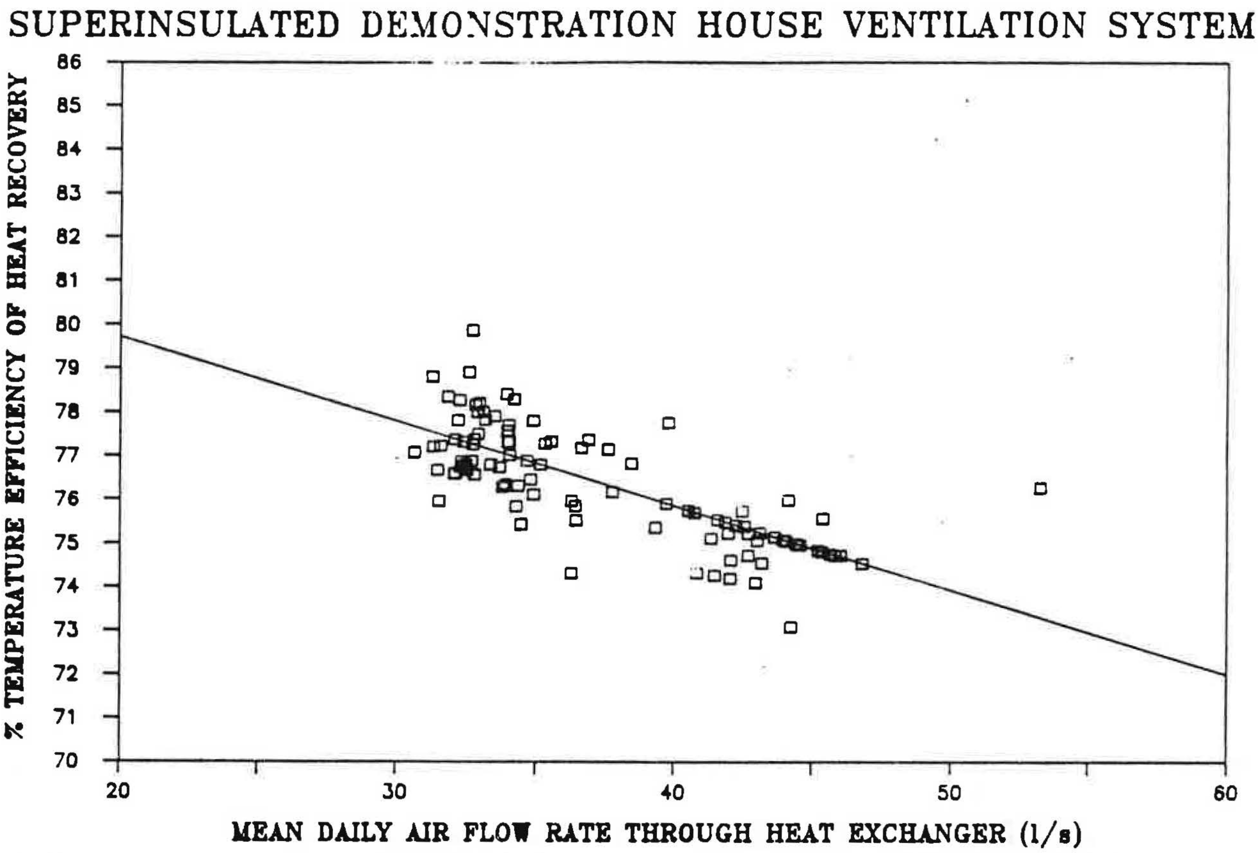

Figure 5 Temperature Efficiency vs Air Flow Rate

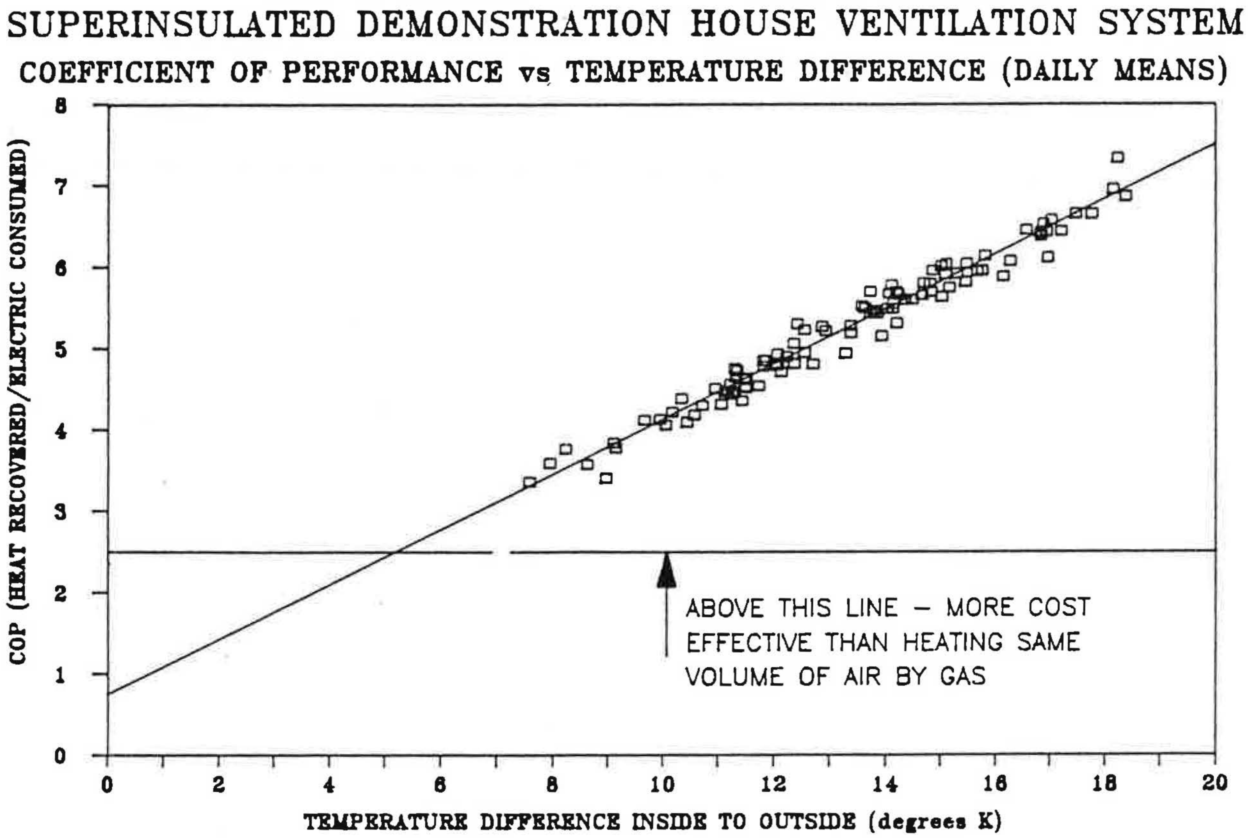

Figure 7 BAHCO Coefficient of Performance vs Temperature Difference

that the temperature efficiency is fairly constant at the 70-80% level. The temperature efficiency appears to depend very little open the temperature difference and a plot of one against the other (not shown here) confirms this observation. Close examination of Figure 4 shows marginally higher efficiencies coincident with lower air flow rates. Figure 5, which plots temperature efficiency against flow rate shows this relationship more clearly. The correlation coefficient of the linearly regressed line in Figure 5 is only 0.46, suggesting other influencing factors. However, the relationship compares favourably with the manufacturers capacity graph shown in Figure 6.

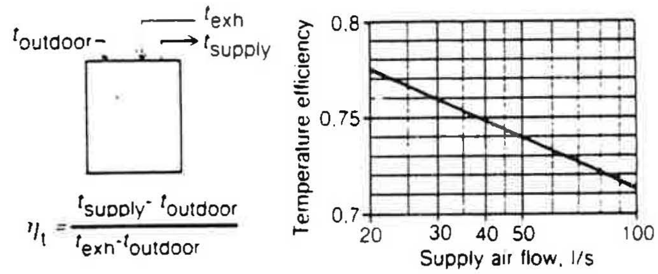

Figure 6 BAHCO Capacity Graph

Coefficient of Performance

As described in an earlier section the coefficient of performance relates the electricity used to the heat input into the fresh air supply. Using the CoP we can establish the cost of the heat supplied to the air per kWh. Taking a time weighted mean of the off-peak and on-peak electricity costs we arrive at a value of £0.04415/kWh. If, for instance, the CoP were 3 then the energy cost would be £0.04415/3 = £0.0147/kWh. The cost of heating by gas using a boiler with an efficiency of 75% is £0.0173/kWh. Therefore, in this example it would be cheaper to use electricity to power the ventilation system rather than heating the same volume of air by gas. However, without using a mechanical ventilation system it would be impossible to guarantee that the same volume of air would be introduced.

Figure 7 shows the CoP of the ventilation system in the demonstration house plotted against the temperature difference from inside to outside. The values given are daily means. The horizontal line indicates the level above which the system is more cost-effective than heating the same volume of air by gas with a boiler efficiency of 75%. As can be seen from Figure 7 all the data points lie above this line, and the resultant saving for the 100 days shown is £9.40. As one would expect from the way it is calculated there is a strong relationship between CoP and the internal/external temperature difference. The interesting feature of this graph is the intersection of the horizontal line and the line of regression for the data points. This occurs at about 5K temperature difference, and suggests that at lower differences it would be worthwhile switching off the ventilation system and opening the windows instead.

CONCLUSIONS

The ventilation system chosen for the superinsulated houses integrates well with the structure, and with one or two minor exceptions was easily installed. The systems are easily accessible for maintenance, which will undoubtedly extend their life expectancy.

Amongst the house owners there is a high level of satisfaction with the ventilation systems. In all the superinsulated houses there is a complete absence of condensation. Several families have remarked upon how quickly misting disappeares after showering, and how venting a tumble drier directly into the house, in order to benefit from the waste heat, presents no problems at all.

The use of the ventilation system to distribute the space heating is not entirely successful. A partially re-circulatory system, or an entirely separate single point heater would possibly be better to suited to the task.

Results from the demonstration house show the temperature efficiency of the heat exchanger to be in the range 70-80% and the coefficient of performance is always greater than 3. At a CoP of 2.5 and above the system is more cost-effective than introducing the same volume of air and heating it by gas at boiler efficiency of 75%.

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