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PERFORMANCE ANALYSIS OF AIR SOURCE HEAT PUMPS USING DETAILED SIMULATIONS AND COMPARISON TO FIELD TRIAL DATA

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ABSTRACT

The take-up of heat pump technologies in the UK domestic sector has lagged far behind other countries in Europe and North America due primarily to the ready availability of cheap natural gas; this has led to the predominance of gas central heating systems in UK housing. However, with recent gas price volatility along with the depletion of the UK's natural gas reserves interest in heat pump technology, particularly Air source heat pumps (ASHPs) is growing as they have the potential to be a direct, low-carbon replacement for existing gas boiler systems. However, to-date there have been few detailed, simulation-based performance studies of ASHP systems.

In this paper a robust, dynamic simulation model of an ASHP device is described. The ASHP model has been integrated into a whole-building model and used to analyse the performance of a retro-fit domestic ASHP heating system. The simulation results were then compared to field trial data.

INTRODUCTION

The UK's international greenhouse gas reduction commitments and national greenhouse gas reduction targets are driving increasingly stringent building regulations such as net "zero carbon" homes (this excludes appliance use) in England and Wales by 2016 (DCLG, 2007) and a target for whole-life zero-carbon homes in Scotland by 2030 (Sullivan, 2007) and an expectation for an 80% cut in CO_2 emissions by 2050 (DECC, 2009a). In parallel, increasing fuel price instability (BBC, 2008), particularly in the price of natural gas is forcing a re-think in the provision of space and water heating in the domestic sector. Close to 80% of the UK's domestic water and space heating demands are met using gas boilers (Shorrock and Uttley, 2008) and it is highly unlikely that the UK's emissions reduction targets could be achieved if this state-of-affairs persists. Hence, there is increasing interest in meeting the heat and power demands of buildings using low or zero-carbon (LZC) technologies such as biomass boilers, micro-renewables and heat pumps. Heat pumps are (belatedly) attracting increasing interest in the UK in that they complement major changes occurring at the larger scale in electricity production: the UK is currently embarking on the development of huge quantities of onshore and offshore wind generation. Heat pumps offer the potential for low or zero carbon heating as the carbon content of grid electricity reduces into the future. Air source heat pumps (ASHPs) are of particular interest in that they have the potential to directly replace gas boilers in existing buildings and can operate in high-density housing (e.g. flats and terraced dwellings). High density housing comprises approximately 40% of the UK housing stock (Shorrock and Utley, *ibid*) and so the potential for retro-fitting of the technology is significant.

Whilst there is an extensive literature on the performance of ground source heat pumps in the domestic sector (e.g. Healy and Ugursal [1997], Kummert and Bernier [2008] in Canada; and Underwood and Spitler [2007], Jenkins et. al. [2009a] in the UK) the literature on ASHP performance is far more sparse. Most modelling work focuses on specific aspects of device performance (e.g. Lui et al [2003], Yao [2004]) rather than integrated performance. In those performance studies that exist, Cockroft and Kelly (2006) used a low-resolution model to determine that in a UK context ASHPs could achieve significant carbon savings in comparison to the domestic heating technologies, including condensing gas boilers. Jenkins et al. (2009b) looked at the carbon savings potential of ASHP in office buildings and concluded that the technology did not guarantee emissions savings under all circumstances; this study used a performance map model of the ASHP and hourly predictions of heating and cooling from a simulation tool.

This paper builds on previous performance studies, specifically attempting to ascertain the magnitude of the achievable carbon savings when ASHPs are retro-fitted into social housing. However, in this case the modelling and simulation is done at a high level of resolution using a detailed model of a dwelling complete with an ASHP heating system, which is run at 1-minute time steps.

FIELD TRIAL DETAILS

It was against a background of increasing interest in heat pump technologies that Scottish and Southern Energy plc. commissioned a field trial of ASHPs in the village of Westfield (55.9 N, 3.7 W) using tenanted properties owned by West Lothian Council, who provided practical support and sponsorship of the project. The objective of this trial was to determine the effectiveness of ASHPs in meeting the space heating needs of the Councils' existing stock of social houses, specifically those elements of the stock reliant on outdated direct electric heating and inefficient coal-fired heating systems. The climate and location of Westfield contribute to a significant requirement for space heating: with the heating season typically running from early September until the end of May. So, in addition to being carbon intensive, the dwellings' heating systems were reputedly extremely expensive to run often leaving tenants in fuel poverty[1]. Hence, one of the key objectives of the field trial and simulation exercise was to investigate potential expenditure through a switch to ASHPs for space heating and how this compared to the alternative retro-fit option of a condensing gas boiler.

A total of 10 houses in the village were retro-fitted with an ASHP system; these were all of similar size and construction (Table 1).

A typical terraced house encountered in the study is shown in Figure 1. The dwelling's external walls were two-leaf, 100mm brick, with a 120mm insulated cavity (the cavities having been previously filled in an insulation upgrade); the walls were rendered externally and wet-plastered internally. The pitched roof comprised concrete tiles lying on top of a bituminous felt and plywood skin, which is supported by wooded trusses. The floors in the dwelling were suspended timber, with a ventilated crawl space under the ground floor.

The ASHP heating system comprised an ASHP unit directly feeding hot water radiators (figure 2) via insulated pipes running under the flooring of each dwelling. The ASHP used had a nominal coefficient of performance of 3.0 with a rated capacity of 8 kW. In these field trials the ASHP served the space heating load only, with the hot water for each house being supplied using an existing 3kW direct electric heating coil, which heated a hot water storage tank; for cost reasons this was not integrated with the ASHP system. However, it should be noted that the device installed should be capable of meeting the hot water load of the dwelling. The radiators were sized for the nominal flow temperature of the ASHP device of 55°C. The flow into each radiator (except a by-pass radiator, typically located in the hall of each dwelling) was controlled by a thermostatic radiator valve (TRV).

Figure 1: terraced dwellings at Westfield

The ASHP was controlled based on the temperature reading from a wall mounted thermostat located in the living room of each dwelling. The set point temperature could be selected by the occupant. The occupants were also free to select the operation time of the ASHP device, select TRV settings, open doors and windows, and to occupy the property as they normally would.

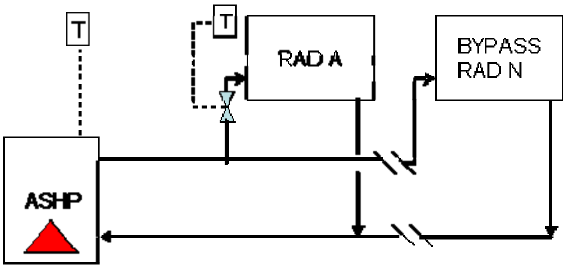

Figure 2 abbreviated schematic of the ASHP and radiator system.

A radio frequency (R.F.) telemetry system, with wireless sensors/transmitters, was installed in each house, with one central receiver/logger. Data was recovered transmitted wirelessly via the GSM mobile phone network. The performance parameters recorded were as follows:

- the electrical consumption of each heat pump was measured using a current transformer clamp on the supply to the heat pump (the instantaneous apparent power consumption was derived by multiplying the recorded current draw in amps by the recorded site mains voltage);

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[1] In the UK the definition of fuel poverty is a household spending more than 10% of its income on fuel bills.

- the total electrical consumption in each house was measured along with voltage (voltage variations affect the performance of the heat pump system);
- the heat output of the heat pump was measured using a heat meter with integrating electronics and a pulse output per kWh;
- outside air temperature and relative humidity were recorded.

Temperatures were measured at three locations (typically the living room, hall and a bedroom) in each house. The transmission interval for all sensors except electrical current clamps was set at 2.5 minutes. The current clamp transmitters were set at a 30 second transmission interval. Monitoring started in February 2008, and stopped in July 2008. Two of the properties dropped out of the study and there were some interruptions due to equipment malfunctions so that a total of 91 days of data was collected for the remaining 8 houses over this time period covering winter, spring and early summer weather; this data is compared later to the results of the simulation exercise.

SIMULATION MODEL

As the monitored data only covered part of a heating season, an integrated ESP-r simulation model (Clarke, 2001) was developed for the building shown in figure 1. The ESP-r model comprised a detailed representation of the dwelling along with an explicit representation of the heat pump and heating distribution system as shown in Figure 2. Each individual room was modelled using a thermal zone and the constructions used in the model were identical to those in the actual building. The building model was also augmented with a zonal air flow model that was calibrated to give the same air leakage rate as that determined from the blower door test of the actual building (approximately 0.5 air changes per hour); in addition to calculating the time-varying exchange of air with the exterior, this model also enabled inter-room air flows to be calculated.

Heat gains for the building model were estimated based on surveys of user behaviour conducted during the field trials and through analysis of the total electrical power consumption of the dwelling; this helped in the estimation of equipment heat gains. Note that the analysis of the electrical demand data also revealed that despite the heat pump providing adequate comfort conditions, a few occupants insisted on employing auxiliary heating devices such as radiant electrical heating enabling them to "simulate" the heating effect of their old coal fire; this was accounted for in the simulations.

The heating system was modelled using an ESP-r plant network. In such a network all of the heating systems components (radiators, piping, valves, etc.) were modelled explicitly. A comprehensive description of the basic heating system models used in this work is given by Hensen (1986) and Clarke (2001).

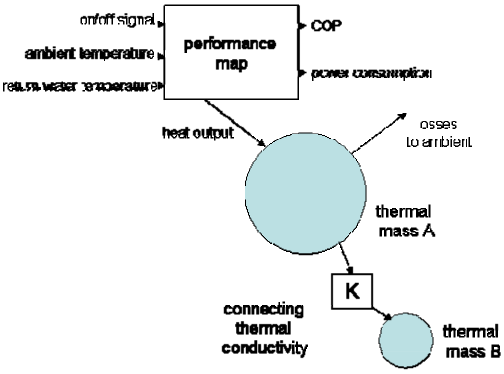

Figure 3 diagrammatic representation of the ASHP model.

A detailed ASHP model was developed for the work reported here that could be fully integrated into the ESP-r building and plant model. From a performance analysis perspective the main requirement for this model was to accurately predict the time-varying electrical demand and thermal output of the device and its explicit interaction the building's envelope, thermal plant, and control systems. Thus, the important elements that needed to be simulated were the variables that couple the ASHP device to the other constituents of a building simulation model, specifically the heat output (hot water), and heat losses. Other outputs of interest included the device's operational status (e.g. on/off cycling, defrost status, temperature compensation, etc.), performance efficiencies, fuel consumption and resulting carbon emissions. Accurately determining these parameters required that the dynamics of the device's heat exchanges were adequately modelled. The representation of the ASHP used in this modelling study (Figure 3) therefore followed the template described by Ferguson et al. (2009), where the device is modelled using a "grey-box" approach in that the model structure reflected the underlying physical characteristics of the device; however, its performance was approximated using empirically derived expressions.

The modelling approach described here has been applied successfully to other domestic heating technologies such as Stirling engine-based cogeneration and internal combustion engine-based cogeneration (Beausoleil-Morrison and Kelly, 2008).

The ASHP model structure comprises three control volumes (Figure 3). The first single volume comprises a series of inputs and outputs linked by a performance map (a series of parametric equations linking the inputs of the model to the outputs). In this case the COP of the ASHP is represented as a 2nd-order polynomial function of the heating system return water temperature and the external ambient temperature difference.

$$COP = f\,(T_{return} - T_{ambient}) \tag{1}$$

The performance map was augmented with algorithms to calculate the defrost status of the device and to modulate the return water temperature set point based on outside temperature. The predicted heat output from the performance map volume was passed to a lumped-capacitance thermal model, featuring two thermal control volumes; these were added to enable the transient thermal performance of the device and coupled heat exchange equipment (condenser and evaporator heat exchangers) to be adequately modelled. The general form of the energy balance for these elements is as follows.

$$M_i c_i \frac{dT_i}{dt} = \sum_{j=1}^{n} \dot{Q}_j(t) \tag{2}$$

Where $M_i c_i$ is the thermal capacity of volume i (J/K); T is its temperature (^oC) and $Q(t)_{1...n}$ are individual heat fluxes at time t e.g. heat loss from the volume to environment; heat flux from another volume; heat lost to coolant, etc.

CALIBRATION

The ASHP model functional block was calibrated using data from independent laboratory performance tests conducted on the ASHP device conducted by BRE Ltd.; these gave performance characteristics over a broad range of condenser and evaporator temperatures. The lumped capacitance elements of the model were calibrated using an iterative parametric identification technique described by Ferguson (2009) with high resolution start-up data from the field trial data.

METHODOLOGY

The simulation of the ASHP system comprised several stages of work 1) the model predictions were compared against the field trial data 2) the model was simulated over a full year and performance data extracted 3) the performance of the ASHP was compared to an annual simulation of a gas boiler system.

Simulations were run over a 1-year time period at a resolution of 1-minute intervals. This resolution was employed to adequately capture the dynamic performance of the heating system featuring the heat pump, particularly with regards to the operation of the control system and operations such as defrost and on/off cycling. Other researchers notably Hawkes and Leach (2007) have indicated that such high resolution modelling is required in order to adequately characterise performance. Finally, as no long-term climate data existed for the Westfield site, simulations were run with an equivalent Scottish climate data set that was representative of the field trial location.

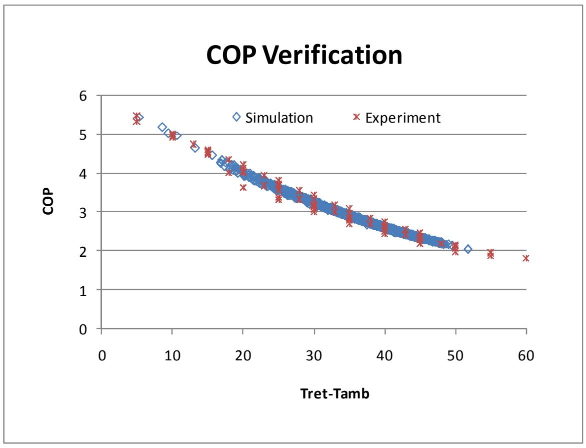

Figure 4 calibrated COP characteristics of the ASHP device.

VERIFICATION WITH FIELD TRIAL DATA

Before simulating performance of the ASHP system when integrated into the Westfield dwelling, the integrated model's predictions were compared to the performance data from the field trial. Figure 5a shows the predictions of COP vs ambient air temperature from the simulation of the ASHP device against the average COP vs ambient air relationship emerging from the field trials; this average relationship was derived from the measured COP values from eight of the monitored houses will be used as representing typical ASHP performance in these types of houses. This averaged relationship represents typical operating conditions for the monitored properties under varying conditions of occupancy. It offers a suitable comparison metric for the results of the simulation model in that the climate and assumed occupancy for the simulation model will differ from the exact conditions experienced during the field trials. A temporal comparison of simulation and monitored results would therefore not be appropriate under these circumstances. Comparing the simulation results to the averaged COP relationship allows a comparison of operating characteristics rather than temporal match to be undertaken.

Comparing the simulation output to the field trial COP relationship (Figure 5a) it is evident that the scatter in the ASHP model output is predominantly above the average COP line: these points are indicative of the dynamic nature of the model and represent periods when the heating system and building are warming up and where the resulting low heating system flow and return temperatures produce a temporarily high COP. However, the highest density of points is close to the average performance line; corresponding with periods in which the heat pump was operating with the return water temperature close to the set point (45°C).

However, the simulation results clearly diverge from the monitored data at higher ambient air temperatures. Subsequent investigation revealed that the temperature compensation facility on the heat pump had not been enabled on the Westfield installations due to an installer error. Consequently, a second annual simulation was conducted with the temperature compensation disabled on the ASHP model. Figure 5b shows the comparison for this simulation and shows that the highest density of simulated results lie on or close to the average COP characteristic from the field trial; this demonstrates that the ASHP device in the ESP-r model operating in under similar conditions to those experienced at Westfield.

RESULTS ANALYSIS

The annual simulation data (with temperature compensation enabled) was further analysed to give an indication of likely annual ASHP performance when retro-fitted into the Westfield dwelling. Figure 6 is a typical example of the high resolution data extracted from the simulations and shows the living room air temperature, heat pump heat output, power consumption and return water temperature during part of a typical winter day.

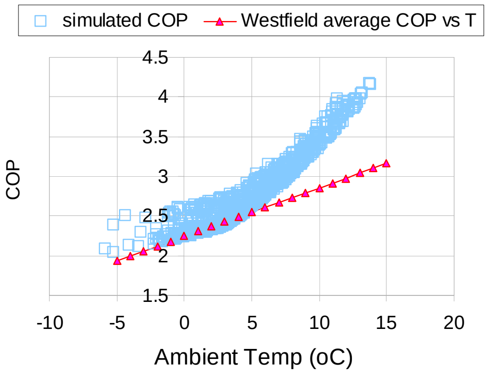

Figure 5a predicted COP vs Westfield average.

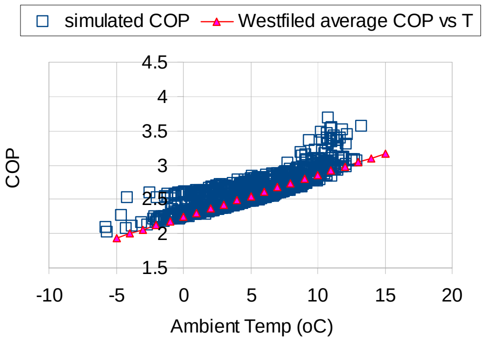

Figure 5b predicted COP (no temperature compensation) vs Westfield average.

Annual performance metrics were extracted from the high resolution data: the average annual COP for the device was approximately 2.7. The estimated energy annual electricity consumption for the ASHP was 2261 kWh (8.14 GJ).

A further simulation was undertaken where the ASHP heating system model was replaced with a model of a gas condensing boiler heating system. Other than the re-sizing of the radiator components to account for a higher supply temperature of 75°C, the system details are the same as those for the ASHP-based system shown in Figure 2. The nominal efficiency of the boiler device model used was 91%, which is typical of a modern boiler being installed in the UK at present. Note that the simulated system efficiency was lower due to parasitic losses.

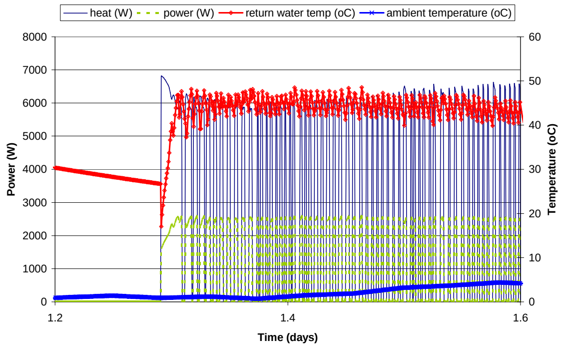

Figure 6 typical winter day results from the simulation.

Analysis of the simulation results indicated an annual gas consumption of 7515 kWh (27.05 GJ or 691.8 m^3) to meet the dwelling space heating load.

Table 2 shows the annual energy consumptions, cost, and CO_2 emissions emerging from the simulations for the simulated house heated using the ASHP (with weather compensation enabled), and the alternative retro-fit option of a condensing gas boiler. Note that CO_2 emissions are based on carbon intensities of 0.19 kg/KWh for natural gas and 0.54 kg/KWh for grid electricity (DEFRA, 2009).

The results indicate that an ASHP installation would produce approximately 15% less CO_2 than a condensing gas boiler installation. This reduction would be greater if grid decarbonisation occurs, however it should be noted that the trend in UK grid electricity carbon intensity has been upwards in recent years rising from 0.52 kg/kWh in 2001 to the current value of 0.54 (Carbon Trust, 2009).

With current UK gas and electricity prices, annual space heating costs using the ASHP are approximately 8% higher than a gas condensing boiler system (£334 in comparison to £309). In this case the ASHP system could only become cost competitive if the electricity/gas price ratio dropped below 3.32 compared to the current level of 3.55 (DECC, 2009b).

It should be noted that both systems would be significantly less expensive to run than the direct electric and coal fired systems replaced prior to the study. For example, direct electric heating would result in an annual space heating bill of approximately £660, whilst space heating using a coal fired room heater would cost approximately £530 per year, assuming a device efficiency of 63% (Hens et al., 2001).

CONCLUSIONS

A combination of simulation and field trial data has been used to assess the annual performance of a domestic ASHP heating system when integrated into social housing in Westfield, Scotland.

A detailed ASHP device model has been developed on the ESP-r platform based on the work of Ferguson et al. (2009) and calibrated using laboratory data. This model was integrated into a whole building ESP-r model of one of the Westfield dwellings.

The model was compared to data emerging from the Westfield field trial; the simulation model was seen to suitably replicate the ASHP operating conditions observed in the field trial.

Comparison of simulation results with field trial data indicated some installation problems with the ASHP device in that temperature compensation has not been activated. Additionally there was some evidence that some householders were employing secondary heating – despite the ASHP installation maintaining adequate comfort conditions.

Simulations were undertaken to estimate the annual energy performance of the ASHP device and an equivalent gas condensing boiler system when retro-fitted into a typical Westfield dwelling. These indicated that:

- The ASHP offered approx. 15% carbon savings in comparison to a gas condensing boiler system using 2009 UK CO_2 emissions coefficients for electricity and gas.
- ASHP running costs were 8% higher using 2009 UK average electricity and fuel prices than a standard gas condensing boiler system.

FURTHER WORK

The work reported in this paper represents the initial stages of the detailed modelling of domestic ASHPs in the UK. A range of additional simulations are being undertaken as part of several follow-on projects to gauge the performance of ASHP devices in a broader range of dwelling types and with respect to future more rigorous insulation building standards.

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Table 1: Westfield house types

Storeys	Type	Date of construction	Bedrooms	Roof	Windows	Number of houses
1	Semi-detached	1969	1	Concrete tile	double glazed	1
1	4-in-a-block flat	1938	3	Natural slate	double glazed	2
2	End terrace	1938	3	Natural slate	double glazed	1
2	End-terrace	1967	3	Concrete tile	double glazed	2
2	Mid terrace	1967-1969	3	Concrete tile	double glazed	4

Table 2: comparison of ASHP and gas condensing boiler system

Heating system	Price of fuel *p/kWh*	Annual Energy use (space heating only) *kWh*	Annual Cost (space heating only) *£*	Annual CO_2 emissions *Kg*
ASHP	12.11	2,261	334	1,221
Gas condensing boiler	3.41	7,515	309	1,429