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Design and testing of a passive solar air pre-heating system for heat pumps using a solar simulator- the Solar Patio concept

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Abstract

Air source heat pumps (ASHPs) are a low carbon technology and are included in the Green Deal and Renewable Heat Incentive scheme as retrofit measure. Their main disadvantage is that their performance is dependent upon the ambient air temperature fluctuations which affect the COP. One way to improve the performance is to combine them with other renewable technologies such as solar thermal. These techniques introduce new elements on houses that might have a negative visual impact on the occupants while serving only one purpose. This study aims to design a solar assisted element that will improve the energy performance of an ASHP while simultaneously being commercially acceptable and serve more than one purposes. A test module was constructed and tested in the Solar Simulator at Loughborough University, while the results were validated against CFD and Dynamic Thermal Simulation (DTS) methods. Additionally, an initial assessment of the energy savings for a typical house made using of DTS, CFD and graphical analysis.

Keywords**:** ASHP, preheating, packed bed, CFD, passive solar, CoP

1. Introduction

Climate change has started to show its effects on the UK temperatures with deadly heat waves in an otherwise cool climate. One of the basic drivers of the planet's overheating is the greenhouse gases that are produced by most human activities. The United Nations tried to find ways to tackle the greenhouse process which led to the creation of the Kyoto protocol. [UNFCCC 1992]. The UK government announced two schemes that would help reduce the CO2 emissions from domestic houses, the Green Deal and the Renewable Heat Incentive (RHI). The Green Deal is a new initiative by the government that is designed to help business and home owners to employ more green technologies in their properties by installing new green technology into properties with no upfront costs. [www.greendealinitiative.co .uk/about-the-green-deal]. The domestic RHI is a financial support scheme for renewable heat, targeted at, but not limited to, off gas grid households. [Domestic RHI statement Policy, 2013]. Air Source Heat Pumps are included in both of them.

1.1 Air Source Heat Pumps

Although the air source heat pump technology is proven to be low carbon, there are some issues though that can reduce the efficiency, increase the payback period and make the users defame them despite of their CO2 emission and financial potential. The performance of the air source heat pump depends on the ambient air temperature, the desired internal temperature and the delivery heating system. When the ambient temperature is low, especially at winter

time, the COP is reduced and there is a possibility that the evaporator would freeze, which will set the heat pump into frost cycle mode increasing increase the energy consumption. The operation schedule also affects the heat pumps performance. In the case where the heat pump's operation schedule follows a typical occupant's working schedule which does not meet the daytime higher temperatures and works over night with the lower available ambient temperatures, further reduces the efficiency of the system even in mid-season times.

1.2 Improvements

There is fair share of research on the improvement of ASHP, either by altering and re-design the operation in order to avoid or minimise the frost cycle, or by combining them with other existing renewable technologies such as solar air heaters and solar thermal collectors. Yongcun, L et al(2011) propose a novel frost-free air-source heat pump (FFASHP) system. This system can realize heating that does not need defrost in winter by extracting heat process from environment. Bertsch, and Groll (2008) compared the performance of different cycles of an air source heat pump under low ambient temperatures, the cascade cycle, the two-stage cycle with intercooling and the two-stage cycle with economizing with the later showing better performance. Ding,Y.et al(2004)was focused on the Reverse-cycle defrosting technique where thermal expansive valve was used as throttle regulator in the unit. A solenoid by-pass valve could facilitate both the defrosting process and the switching process after the termination of the defrosting process, and best performance could be addressed if it's energized during the whole defrosting time. All the above studies were focused on improving of the operation within the ASHP. and are valuable in the industry of heat pumps as they point out the need to reconfigure the ASHP design to a more appropriate for cold climates. But this holds little meaning for those who already use ASHP since all of the above approaches cannot be used as an upgrade to an existing heat pump.

On the second improvement approach, Lu et al (2009) proposed a solar assisted air-source heat pump with solar collector in a parallel-connected, non-direct expansion system. The study concluded that the solar assisted air-source heat pump system is a feasible technology; The performance of this system depends on the solar collector efficiency, area and an appropriate water tank sizing (50-100 litre/m2 of collector area) .Similarly, Liang, C. et al (2011) studied the performance of a solar assisted air source heat pump system for building heating, where compared with the case when the solar collector area was 0 m2, the COP increase of the heat pump and the energy saving rate were at 24% when the solar collector area was 40 m2. In these studies, the heat exchangers, water storage tanks and pumps introduce high costs and maintenance as well as additional space within the house. These systems are found most suitable for countries like China or the regions of South Europe where solar radiation levels are higher than UK's.

Karagiorgas, M. et al [2010] investigated the performance of an air source heat pump connected with an existing air solar heater in the bioclimatic building in Greece. In this study, the existing solar air heaters were used to redirected the warn air onto an ASHP and although it took place in a warmer climate than UK, the proposed approach could be easily implemented into a residential retrofit but with a lower efficiency. But since there is no storage heating, the energy saving should be realised if the building is used during day time for example if the occupants were pensioners. In addition, the cost of having placed black solar air heaters on the south external walls or the roof should be high and would probably become visually unattractive for the occupants.

2. The Solar Patio concept

The difficulties on the application of solar assisting ASHP systems in the UK housing stock could be transcended by the creation of a new passive solar building element that could

involve more parameters relative UK domestic building reality.The Solar Patio (SP) generally is a passive solar version of the typical patio connected to the external unit of an ASHP(Figure 1). Its main function consists of two operation modes:

- During day is solar collection and storage. It performs as a solar air heater in stagnation, where there is no air flow from the patio and storage of the solar energy to the bottom, where there is a layer of material with high thermal capacity such as bricks, rocks, concrete blocks etc.
- During evening and night, when the ASHP would be in operation, the SP acts as a packed bed, where it lets ambient air to flow through, absorbing the stored heat and raise its temperature. The pre-heated air ends up to the heat pumps evaporator at higher temperature than the ambient, improving the performance compared to the no pre-heating operation.

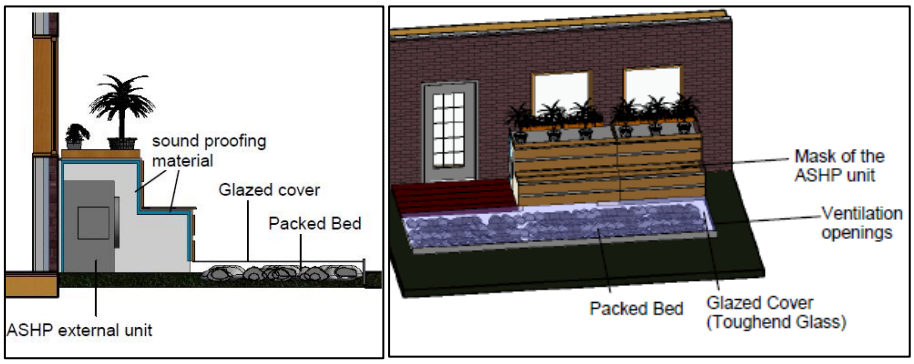

Figure 1. Basic parts of a Solar Patio

The operation of the SP is set to match the actual operation of working occupants. A secondary objective is to stretch the available pre-heating beyond the time when the off-peak tariff starts. This requires further study though, to find the ideal relation between thermal mass, heat transfer coefficients, air flow paths and solar gain optimisation. The top surface of the SP consists of a single glazed cover, made from toughened glass in order to allow people to step on it. SP glazing is horizontal so it does not require proper orientation as other solar systems do. This gives 90% solar irradiation efficiency, regardless of orientation, except the North. Of course shading from trees, fence or the house itself may affect the performance, so distances from obstructions should be kept. The heat storage system of the SP consists of materials with high specific heat capacity such as rocks, bricks and concrete blocks. The top surface that will absorb the solar radiation should have high solar absorptivity, for example 0.9 for black surfaces. The arrangement of the material should be done in a way that will create air flow paths over and within the heat storage layer so that the heat transfer to the ambient air, during the heat pump operation, would be sufficient, for example the choice of different sizes of pebbles or bricks with holes, creating tubes when they are put together. The choice of the solar absorbing surface of the packed bed has more available options. Although black colour has the highest absorptivity (0.9), it is usually avoided in living spaces unless it is made to fit from the design stage with the rest of spaces. A variety of dark colours could be used, such as dark green, blue and red, despite the fact that they have lower solar absorptance. The Solar Patio can perform as a display element by using several types of surfaces such as Chess-like tiles, mosaic shapes or even paintings. Another attribute of SP system is that it can mask the external unit reducing the visual and noise impact. The patio can also become a tool for landscaping of the front/backyard to the personal artistic taste of the occupant.

3. Methodology

In order to study the performance of this new system, without previous knowledge or benchmarks the following methods were chosen:

- Laboratory experiment: with the use of the Solar Simulator in the laboratory to represent the sun and a fan to represent the ASHP, a SP module was tested under controlled environment which will recreate certain conditions of an expected typical performance and operation. The test module was a wooden box with dimensions 1/10 of the Solar Patio (0.85m x 1.0m x 0.2m). The box was internally insulated with 0.05 m of fireproof thermal insulation (0.035 W/mK). A toughened glass cover of 8mm was place on the top and tree columns of bricks with holes were fit in the box. A single layer of red bricks with holes which create internal tubes, acted as packed bed. The box was placed against the solar simulator and connected to a fan via a circular flexible duct. Eight thermocouples and a radiation sensor were placed in key positions for the most representative readings
- The two modes of SP operation were simulated in Phase1 (solar heating/storage, Solar Simulator ON, fan OFF) and Phase 2 (air-preheating during evening operation, Solar Simulator OFF, fan ON). The temperatures of the single layer of bricks (surface, middle and back), the inlet and outlet air were monitored and calibrated.
- Dynamic Thermal Simulation (DTS) was used to validate the measurements that were obtained from the Phase 1 of the experiment (solar heating and storage) and investigate possible improvements. An IES VE model with a tempered weather file was employed for this purpose.
- CFD simulation was used to validate the measurements that were obtained from the Phase 2 of the experiment (air pre-heating, outlet air temperature), with the use PHOENICS software.
- Combination of CFD, DTS and graphical analysis from manufacturer technical data sheet was used to estimate annual energy savings in as well as possible improvements. Average ambient and internal surface temperatures of the SP were calculated during the operation schedule for each month (17:00-24:00) , for London area weather file. These monthly averages were imported as inputs on the CFD model and the average outlet air temperatures from the SP to the ASHP were derived. These average air temperatures were plotted over the technical data sheet graph (COP-ambient) of the ASHP and the new COPs were estimated for each month. Lastly, a typical UK house model was made where the energy consumption for heating, was based the monthly COPs due to the SP and due to the ambient. The difference between the consumptions gave an initial estimation of the electricity savings.

4. Results and discussion

4.1 Experiment

During the experiment there was an AC failure so that there was no control over the room's temperature/ambient, where the average temperature levels in the end of phase 1 was 28oC . For various reasons, the irradiance levels were set rather high (660 w/m2) which represent a typical summer day in UK. These conditions prevented the simulation of a typical midseason day. The data's worth is focused on a comparative review and analysis. The calibrated temperature results of Phase 1 showed that natural convection within the box reduced the heat transfer to the back of the bricks. Thus, the time hysteresis between the middle and back layer was increased during the experiment. Phase 2 results showed that the pre-heating lasted for almost 40 minutes, until inlet and outlet temperatures became equal. The primary heat transfer mechanism was located between the surface of the bricks and inlet air(ambient). There was a minimum difference between the average brick temperature and the ambient temperature of 5oC, below which the outlet air temperature is not increased and the effectiveness of the system is stopped. The Uncertainty Analysis on the thermocouple accuracy, showed that the reliability of the results, especially in Phase 2, must be taken in

consideration, as the reliable range of results and the effective air pre-heating period is reduced.

4.1 CFD simulation

The CFD model was set up in PHOENICS (Cham), based on temperature conditions that were taken by the experimental Phase 2. CFD simulation showed results consistent with the experiment or at least explainable, and the effect of the wooden head of the box, as an additional heat source, was identified.

4.3 Dynamic Thermal Simulation

The results of Phase 1 of the experiment will be validated by the use of dynamic thermal simulation. For this purpose, a dynamic thermal model has been prepared with IES software. For the study purpose, a tempered weather file was used to simulate the experimental conditions. The IES model showed an average 11.8% difference of the experimental values due to various possible reasons that could originate either from the modelling or the experiment or both. The approach of tempering the weather file, created uncertainties in relation with the time step that could be avoided with the use of other research simulation software such as Energy Plus or ESP-r.

4.4 Annual Energy Savings Estimation

All the results were based on average temperature values and although they were calibrated according to experiment conclusions, there is chance of errors and uncertainties since the IES model worked with absolute values. Again, the importance of the conclusion lies in a comparative analysis. The CFD model is assumed to perform well according to the experimental validation. The interpretation of the heat pump's COP graph also, left room for more errors due to the scale and small temperature values. The Solar Patio system, showed a relative small electricity savings for September (0.69%), March (1.06%), April (2.28%) and May(1.64%). A change in the solar absoptance of the surface and a control in the natural convection increase the saving by little (September 1.2%, March 1.2%, April 2.4%, May1.7%). The savings do not include savings from but the frost cycle consumption. Flexibility on the operation schedule could improve the performance. The schedule of the SP is of key interest, since the ASHP must follow the occupants working schedule, which might not match the best performance especially after sunset, when the ambient air becomes colder. The stored heat into the packed bed can be utilised during night. Alternative operation schedules may increase the performance of the SP

5. Conclusions

- The performance of the system depends of solar heat gains and storage. The heat storage system of the SP consists of simple and widely available materials with high specific heat capacity such as rocks, bricks or concrete blocks, so it is easy to build without significant manufacture process. The solar absorptivity play important role with a dark coloured surface to be more effective. The surface of the packed bed could serve additional commercial role as it could become an artistic display exhibit. A secondary feature involved the masking of the external unit in a way that it could reduce the noise transmission and affect the appearance.
- In general, performance of the SP, was relative low, and was focused on mid seasons, and having a reversed role during winter months. An increase in the solar absorbptance of the packed bed e.g. painted black, along with the reduction of natural convection, increased the performance, only by little(around 1.2%)

- The schedule of the SP is of key interest, since the ASHP must follow the occupants working schedule, which might not match the best performance especially after sunset, when the ambient air becomes colder. The stored heat into the packed bed can be utilised during night. One of the desired functions of the SP is to assist the performance of the ASHP that operates with off-peak tariff electricity. The initial simulation analysis showed that the system would not be that efficient when the ASHP operating from 00:00 to 06:00 compared to 17:00-24:00 schedule.
- It must be noted though, that all the simulations and conclusions were based on the minimum amount of Solar Patio modules, with the same characteristics as the lab test-module, that are required to cover the maximum air flow rate of the ASHP. Since most of the ASHPs have variable fan speed, the heat transfer coefficient of the SP would also be variable. Furthermore, if more modules have been used, it is almost certain that the air pre-heating could be more efficient. The results of the low performance should not be considered as a characteristic of Solar Patio but rather as early conclusions in a developing concept that could be used as a starting point for further studying.

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