TESTING A PROTOTYPE GAS-FIRED RESIDENTIAL HEAT PUMP

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Abstract: A new gas-fired absorption heat pump has been developed for residential application, providing both space heating and cooling. ECN has tested a prototype in one of its research dwellings. A direct water-to-water configuration was applied for heating, for cooling an indirect air-to-air configuration. Both ground heat exchangers and outdoor air have been applied as energy source. The experiments showed promising results, regarding energy performance, thermal comfort and reliability. Furthermore two cooling distribution systems have been compared: air cooling versus floor cooling. Compared to air cooling, the floor cooling reached similar thermal comfort (and cooling power) at a significantly higher supply temperature (generally resulting in a better energy performance for heat pumps).

Key Words: ***gas-fired, absorption, heat pump, residential, monitoring***

1 INTRODUCTION

Given the current EU ambitions for a more sustainable energy supply system, heat pump technology is expected to gain further importance the coming years. Recognizing the possibility of providing high thermal comfort combined with high energy efficiency, together with the potential of energy savings in existing building stock, a new gas-fired residential heat pump has been developed recently. The company developing this heat pump will remain anonymous in this paper.

After encouraging results from laboratory experiments and a preliminary field-test (2003-2004), a first prototype of the gas-fired heat pump was improved, resulting in a very compact second prototype. Having the desired “real life” research facilities and analysis tools, ECN was asked to test this prototype in one of its research dwellings.

The gas-fired heat pump can be used with different sources (e.g. air and ground) and distribution systems (air and underfloor). This paper presents the results from experiments with all these options, for both heating and cooling mode.

In countries with dense gas grids, such as The Netherlands and other European countries, gas-fired absorption technology is an interesting option. The technology offers significant energy savings and optional cooling, compared to the common HE gas-fired boiler. Furthermore it requires a relatively small ground or air source compared to compression heat pumps and it does not have noise issues related to compressors. However, until now there are only few products available for single family houses.

2 THE HEAT PUMP

The heat pump described here has been developed especially for residential application, focussing on both new houses and existing building stock. The heat pump is based on an absorption cycle using natural gas to drive the cycle (= to provide heat to the generator).

The tested prototype (figure 1) is wall-mounted and relatively compact (volume of about 0.21 m^3 at a weight of 80 kg). The supply temperature for space heating of the tested prototype can be varied between 35 and 50 °C. The thermal output modulates between 2 and 4 kW.

Figure 1: Heat pump prototype (with HE boiler on the right)

3 TEST SET-UP

The heat pump has been tested in one of the research dwellings located at the ECN premises in Petten, shown in figure 2. These houses represent the typical row house as commonly built and used in studies in The Netherlands. The gas-fired heat pump was applied in "dwelling B", the second house from the left in figure 2.

Figure 2: ECN research dwellings, where heat pump was tested

Some characteristics of these research houses are: south orientation, well insulated (R_C > 5 $m^2 \cdot K/W$), air-tight envelope ($q_{v;10}$ < 40 liter/sec), highly efficient glazing (U_{cog} < 0.9 $W/m^2 \cdot K$), living area with large glass surface, solar shading on first and second floor, balanced ventilation with high efficiency heat recovery and four different low temperature distribution systems (air, floor, wall and radiators, which can be used for both heating and cooling).

The houses are not inhabited, but "average" occupant behaviour is simulated with weekly patterns for internal load due to use of household appliances and presence of people, use of domestic hot water, ventilation and temperature set points, and CO_2 and humidity production.

The top floor (attic) is not directly heated or ventilated and is used to install all HVAC components.
An extensive monitoring system records all energy flows (heat and electricity), climate data (irradiation, wind, ambient temperature and humidity), temperatures (indoor air, building mass and water flows) and other comfort criteria, such as humidity and CO_2 levels.

3.1 Winter configuration

The heat pump is connected to vertical heat exchangers (ground source) and provides heat to the dwelling using a floor heating system (direct water-to-water heat pump). A standard high efficiency gas-fired boiler supplies domestic hot water. The system configuration is shown in figure 3.

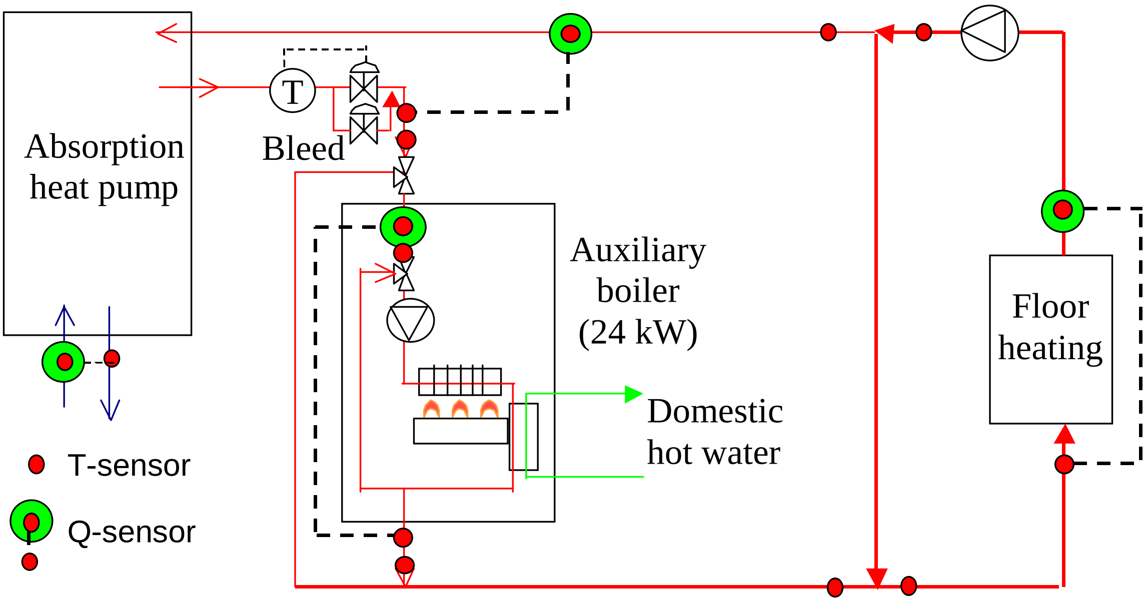

Figure 3: Heat pump configuration during winter season

Due to the measures mentioned above, the demand for space heating is very low in the dwelling. To get sufficient measurement data, the heating demand was increased using a bypass on the heat recovery in the ventilation air. The thermostat that controls the heat pump is mounted in the living room. The set point has been continuously 21 °C. To maintain the correct physical condition for the absorption process inside the heatpump, the heat pump control is set to provide a constant supply temperature of about 35 °C. Performance has been measured over a period of 12 weeks (February-April).

3.2 Summer configuration

After the heating experiments in winter, the heat pump configuration was changed to test cooling performance. The heat pump was configured as an indirect air-to-air heat pump; the evaporator cools ventilation (+ recirculation) air via a heat exchanger and ambient air cools the condenser via a heat exchanger. Special measures were taken to collect condensed water vapor from the air-to-water heat exchanger and from the heat pump. Figure 4 shows a schematic of the configuration.

The cold air, in total about 280 m^3/hr, is distributed to the three bedrooms, the kitchen and the living room. The solar shading and ventilation unit with heat recovery is used to reduce the cooling load on days with high irradiation and/or high ambient temperatures. Performance has been measured over a period of 7 weeks (July-September).

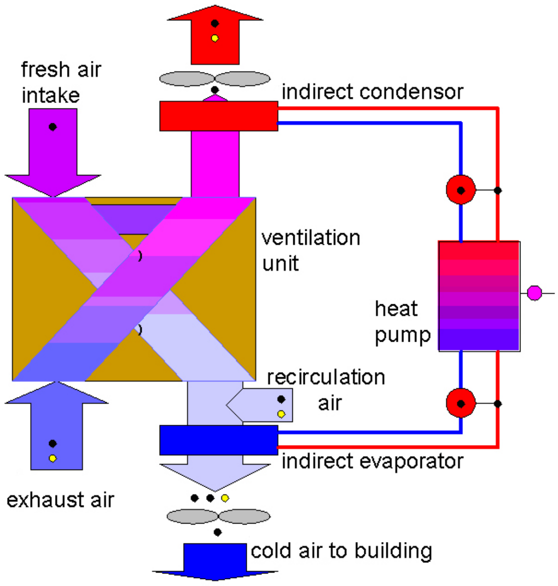

Figure 4: Heat pump configuration during summer season

4 TEST RESULTS
4.1 Winter

During the test period the average outdoor temperature was about 4.2 °C, the minimum was -5.8 °C and the maximum 17.3 °C. Figure 5 shows the measured ambient temperature.

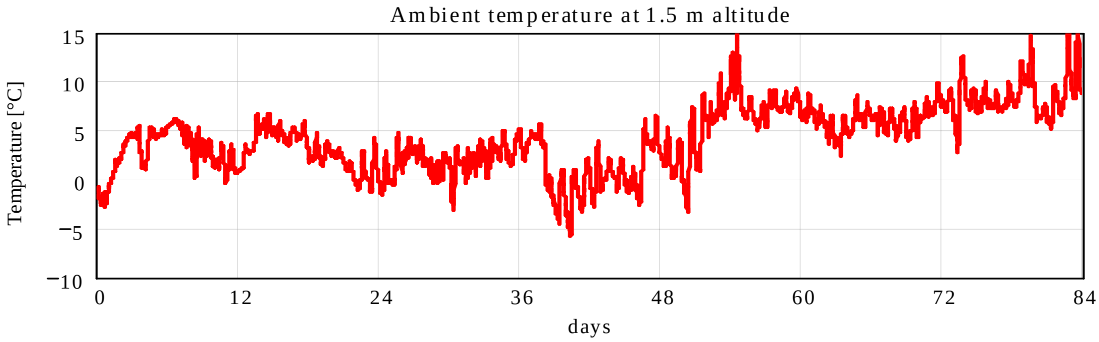

Figure 5: Ambient temperature during winter season

Figure 6 shows the heat pump energy balance during winter season, where "space heating only" data is considered. Electricity consumption (pumps, controls, etc) of the heat pump is about 5 % of the total energy input. By optimizing the electronics and pumps it's expected this consumption can be significantly reduced. The ratio between the total amount of delivered heat and the necessary energy to supply this heat (gas and electricity) is 1.1. The energy output shows useful heat delivered and energy losses (22%) at a system level.

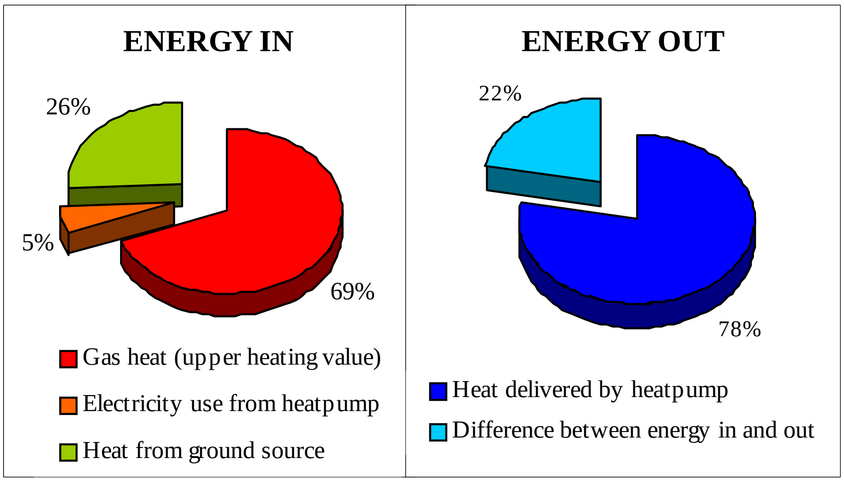

Figure 6: Heat pump energy balance during winter season

The Coefficient of Performance (COP) characterizes the energetic performance of a heat pump. To determine the average Coefficient of Performance (COP) only steady state operation is considered, defined as the ratio between thermal output and gas input [1] when the thermal output > 2 kW.

The daily average COP based on the lower heating value (LHV) measured during the field test is 1.45. This value has been very constant during the test, as illustrated in figure 7 (month February). During this month the ground source temperature varied between 6 and 8 °C, resulting in an average temperature lift for the heat pump of 28 °C.

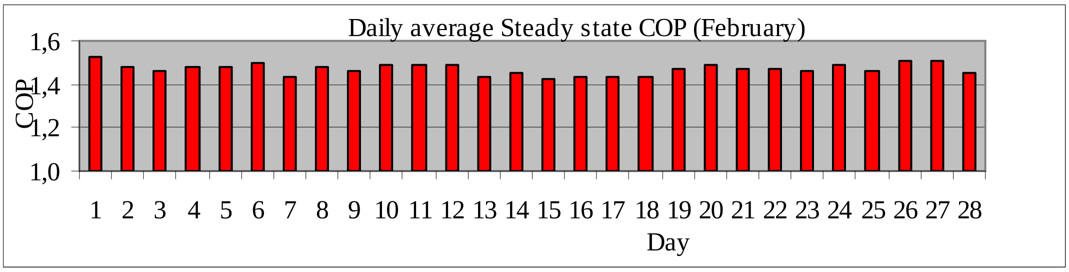

Figure 7: Heat pump COP (steady state, LHV) for heating during month February

The data from March and April indicates that increased on-off switching, when the heating load is very small, reduces the COP: over the total field test period, the overall COP is about 10-15 % lower than the steady state COP.

The heat pump modulates its power to provide a constant 35 °C supply temperature. Peaks of almost 4 kW_{th} have been registered but the working point was typically about 2.5-3 kW_{th}. The data indicates good part load behaviour.

The accomplished temperature levels in the dwelling meet comfort criteria and the thermostat set point (living room not below 20 °C). The sound levels produced by the absorption heat pump are acceptable (similar to the gas-fired boiler).

[1] The amount of heat produced by gas combustion depends on the quality of the gas and the burning process. Only the caloric value of the gas is measured, defined in the so-called upper heating value (~36 MJ/m_n^3; full combustion of 1 m_n^3 gas including condensation of the water vapour).

Application of the absorption heat pump under these conditions resulted in significant savings for space heating: under steady state conditions this heat pump is about 35 % more efficient than a standard HE gas-fired boiler (with 107 % efficiency at lower heating value).

4.2 Summer

Ambient temperature was on average 17.7 °C during this cooling experiment, the maximum was 27.9 °C. Figure 8 shows the heat pump energy balance during summer. The ratio between the total amount of extracted heat from the evaporator and the necessary energy for the heat pump (gas and electricity) is 0.37. Transforming the measured values to primary energy, the average performance factor becomes 0.35.

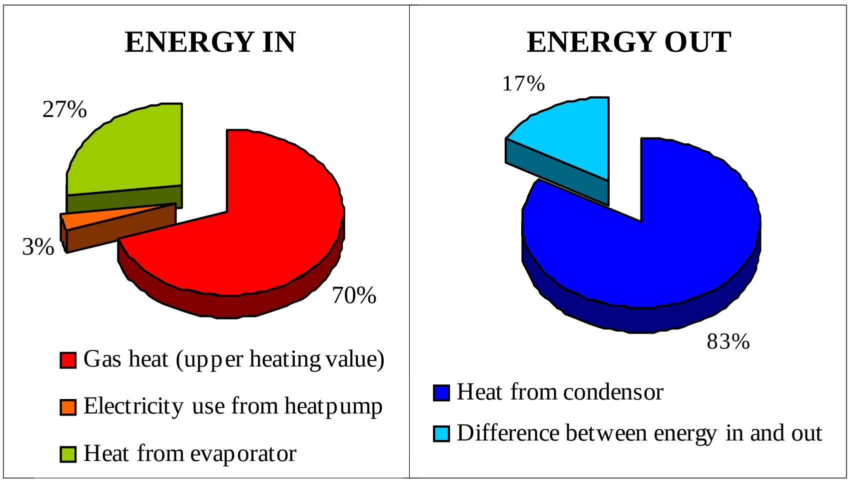

Figure 8: Heat pump energy balance during summer season

The COP for cooling is defined by the ratio of extracted heat at the evaporator side and the necessary (thermal or electric) input for the heat pump. The thermal input is determined as described above (test results winter). To determine the average Coefficient of Performance (COP) only steady state operation is considered, defined as the ratio between thermal output and gas input when the gas input > 3 kW. The daily average COP based on the lower heating value measured during the field test is 0.43. This value has not been very constant during the field test, as illustrated in figure 9.

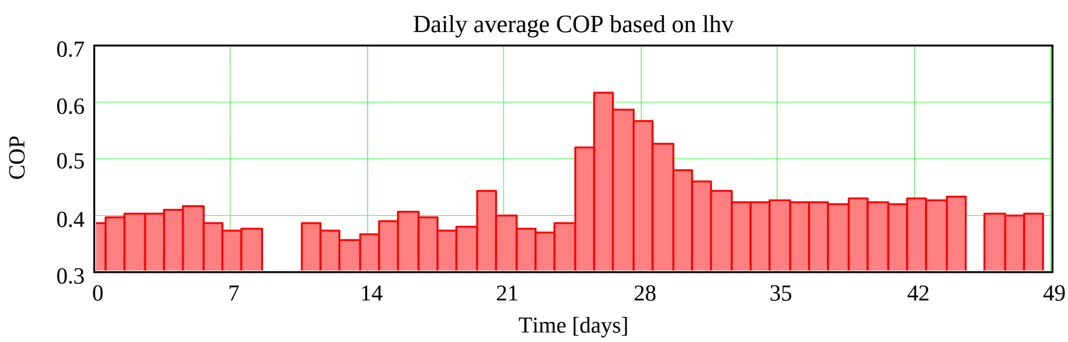

Figure 9: Heat pump COP (steady state, LHV) for cooling

The relatively high COP's measured on day 25 to 32 are possibly caused by an increased airflow over the evaporator. Before the adjustment of the air flow, the daily average COP was around 0.39. This increased to around 0.42 after the adjustment, after an initial increase to more than 0.5.

The cooling power was on average 1.5 kW, but there were also incidental peaks of up to 3 kW (during which the COP approached 0.8). The temperature of the cold air typically varied between 10 and 15 °C.

5 COOLING: FLOOR VERSUS AIR

Due to the increasing demand of thermal comfort, domestic cooling becomes more and more an issue in The Netherlands and other European countries. In The Netherlands an annual growth of the air-conditioning penetration between 10 and 15 % is expected [1].
Application of a sorption heat pump allows two different kinds of cooling. In one of the research houses experiments were done that allow comparison of air cooling and floor cooling, looking at both energy performance and thermal comfort [3]. The experiments were intended to answer the question which of the above mentioned ways to provide cooling to a room provides equal thermal comfort with higher chilled water temperatures. The chilled water relates directly to energy use because it determines the temperature lift and therefore the performance of the heat pump.

5.1 Experimental set-up

For the air cooling system, chilled water is produced (by a small absorption chiller) with a supply temperature varying between 6 and 9 °C, cooling the ventilation air flow to the building via a water-to-air heat exchanger. Because of the relatively low chilled water temperature, dehumidification of the air flow will occur (in the heat exchanger). To provide enough cooling, the air flow (for ventilation) is increased by recirculation of air.
For the floor cooling a standard underfloor heating/cooling system was applied with "chilled" water from ground heat exchangers (free cooling). The chilled water has a supply temperature of 18 to 23 °C. Because condensation of water vapour on the floor is not desirable, dehumidification is not an option.
Both experiments took place in research house B, described earlier. And both cooling systems delivered an average cooling power of about 1.5 kW.

5.2 Evaluating thermal comfort

The theory of Fanger [2] is used to evaluate thermal comfort, in which the so-called Predicted Mean Vote (PMV) is used as indicator. Inputs for the calculation of the PMV are mean radiation temperature, relative humidity, air temperature, metabolic rate, clothing and air velocity. For more details on the PMV the reader is referred to [2].
All temperatures and relative humidity are provided by the experiments. The others inputs are assumed according to table 1.

Table 1: Assumed constant inputs for PMV calculation

Input for PMV	Value
Metabolic rate (domestic work)	1.7 MET = 98.9 W/m^2
Clothing factor (summer = 0.4, winter = 1)	0.4 = 0.062 m^2·K/W
Air velocity	0.12 m/s

The parameters clothing and metabolism have the strongest influence on the PMV. Since they are kept constant in this study, the air temperature becomes the determining parameter, as can be seen in figure 10.

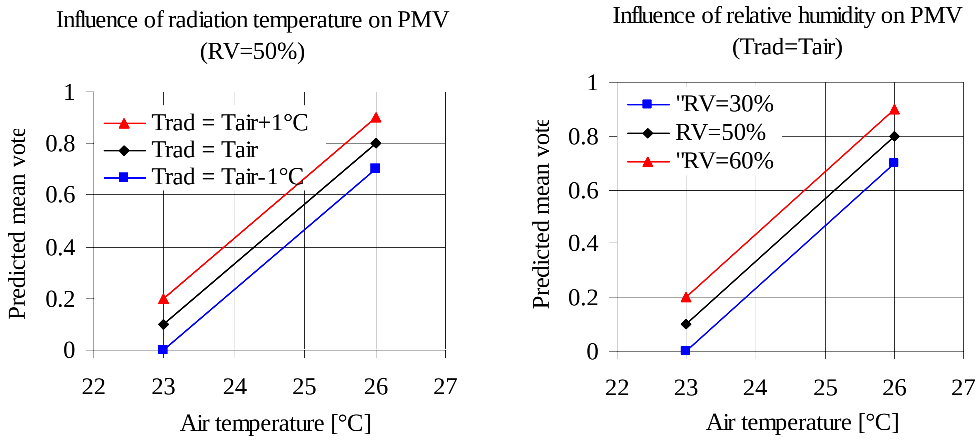

Figure 10: Influence of measured parameters on the PMV

5.3 Experimental results

The experiments have been done in the same house, but in different years. During the air cooling experiment, ambient temperatures and solar radiation were higher compared to the period the floor cooling was tested.
Floor and air cooling provide similar average cooling power, but with a 12 °C higher chilled water temperature for the floor cooling. Figures 11 and 12 show for both systems the cooling power versus chilled water temperature (left) and the PMV versus living room air temperature.

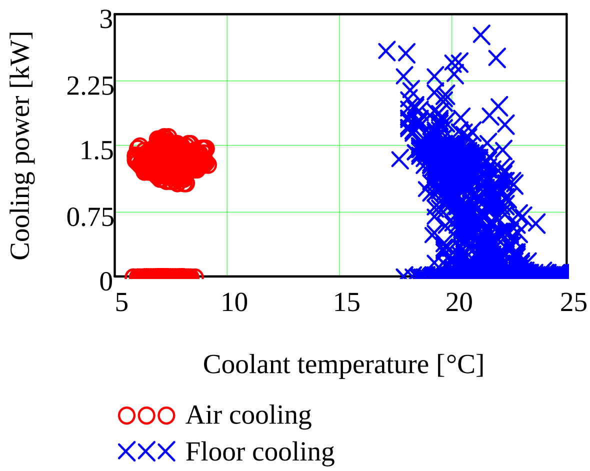

Figure 11: Cooling power versus chilled water temperature during day time

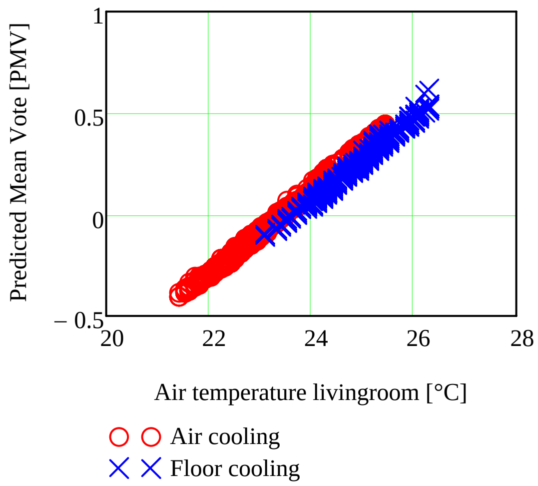

Figure 12: PMV versus air temperature during day time in living room

The graphs show that with similar air temperatures in the living room, floor cooling with a chilled water temperature between 18 °C and 23 °C results in a similar effect on the PMV as air cooling (with a chilled water temperature between 6 and 9 °C).
With above mentioned conclusions, it is clear that for Dutch climate conditions, floor cooling provides similar thermal comfort compared to air cooling using the standard ventilation

system while it operates at much higher chilled water temperatures. The comparison made in this study of course does not allow conclusions on dynamic effects (response time for floor cooling versus air cooling) or on the possible difference in thermal comfort under “extreme” climate conditions (e.g. very high relative humidity).

6 CONCLUSION AND OUTLOOK

The tested absorption heat pump showed reliable operation and promising energy performance. In (direct water-to-water) heating mode, a fairly stable COP was measured, on average 1.45 (steady state) at a temperature lift of about 28 °C. The performance in (indirect air-to-air) cooling mode reached values of more than 0.5, but the performance varied significantly and can be improved (e.g. by improving heat transfer in the air handling unit). The heat pump has shown flexibility in sources and distribution systems, and good part load performance.

Given the energy performance and other advantages, gas-fired heat pumps, such as recently shown at ISH 2007 (figure 13), could make a significant contribution to increase energy efficiency in both new and existing buildings, when compared to HE gas-fired boilers. The comparison with electrical heat pumps is strongly influenced by the national situation concerning e.g. efficiency and emission of central power production, and the availability of green gas.

For the prototype described in this paper, different configurations were tested to investigate the capabilities of the design. This provided information for further development. The next prototype is expected to have improved energy performance and to be a significant step closer to the market.

The authors wish to thank the developers of the heat pump for the opportunity to publish on this interesting development.

Figure 13: Example of residential gas-fired heat pump, presented at ISH 2007

7 REFERENCES

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8 ABBREVIATIONS

COP	Coefficient of Performance [-]
HE	High Efficiency (refers to state of the art condensing boiler)
LHV	Lower Heating Value (of natural gas) [MJ/m^3]
MET	Metabolic Rate [W/m^2]
PMV	Predicted Mean Vote [-]
Q	Energy (heating or cooling) [kWh]
$Q_{v;10}$	Indicator for infiltration rate (air leakage at 10 Pa difference) [lit/sec]
R_C	Thermal resistance of construction element [m^2·K/W]
RV	Relative humidity [%]
T	Temperature [°C]
Tair	Air temperature [°C]
Trad	Radiation temperature [°C]
U_{cog}	Thermal conductance at center of glass (no frame effects) [W/ m^2·K]