Preliminary Findings on the Performance of a New Residential Solar Desiccant Air-Conditioner

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Abstract

CSIRO and Rinnai have developed a new prototype 3-in-1 solar product designed to produce hot water, supply winter space heating; and provide summer space cooling. The cooling component of the system uses desiccant cooling technology. TRNSYS modelling predicts that thermal energy savings of more than 50% can be achieved in a typical Australian household. A prototype of the product has been constructed, and initial testing of the desiccant cooling component found that the desiccant cooling system reduces building supply air temperature by around 6°C under design summer conditions.

Keywords: Desiccant cooling, Solar airconditioning, Residential energy

1. Introduction

Desiccant cooling is a thermally activated cooling technology with considerable promise in solar airconditioning applications [1]. A number of recent installations have demonstrated the technical feasibility of solar desiccant cooling and, in some cases, desiccant cooling offers the potential to achieve high performance (COP>1) [2-3].

CSIRO and Rinnai have developed a prototype solar residential desiccant air-conditioner product. The product is intended to satisfy three important and energy-intensive functions in the home, that being the production of: i) hot water all year round; ii) hot air for winter space heating; and iii) cool air for summer space cooling. A schematic of the concept is illustrated in Figure 1.

Key advantages of desiccant technology in residential applications include:

- ***Robust Technology*** **–** desiccant systems offer a low-maintenance, easy to maintain solution
- ***Cooling tower not required*** **–** no special maintenance and monitoring schedule is needed
- ***Efficient operation using low temperature heat*** **–** (such as that from flat plate solar collectors)
- ***Operates when heat is not available -*** can operate in stand-alone evaporative cooling mode when solar heat is not available. This provides additional cooling hours without the need for significant thermal storage. This is particularly important on hot summer evenings when occupants return home from work.

This paper describes some of the initial modelling and testing work performed at the CSIRO Energy Centre in Newcastle, Australia.

Figure 1: CSIRO and gas appliance supplier Rinnai have developed a new 3-in-1 solar product designed to produce hot water, supply winter space heating; and provide summer space cooling.

2. TRNSYS Modelling

A flow diagram of the selected prototype desiccant cooling cycle is illustrated in Figure 2.

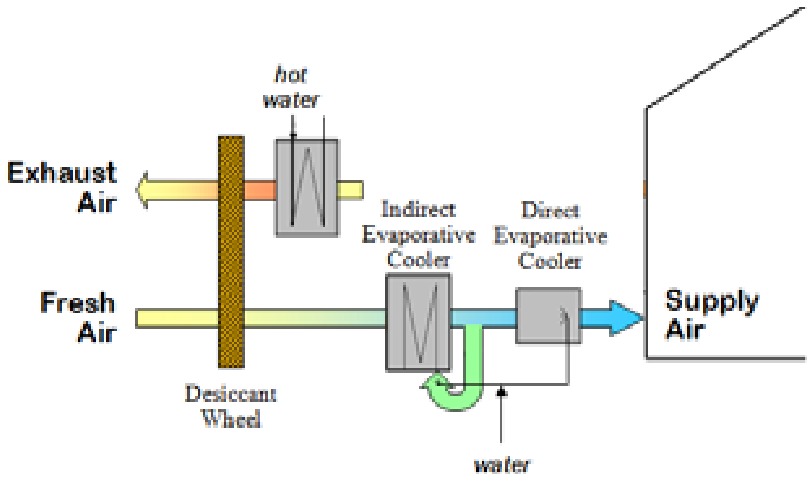

Figure 2: Flow Diagram of the Selected Desiccant Cooling Cycle

In this cycle, as fresh outside air is dried using a desiccant wheel it is unavoidably warmed, due to the adiabatic drying process. The warm dry air stream is then cooled to temperatures below ambient using a two stage (indirect/ direct) evaporative cooling process before it is introduced into the occupied space to provide the desired space conditioning. Outside air is then heated by a heating coil using solar heated hot water and is used to regenerate (drive moisture from) the desiccant wheel.

The cycle was principally selected for its simplicity, low cost and low pressure drop (which results in low parasitic fan power consumption). Given the anticipated low regeneration temperatures, the absence of a heat recovery heat exchanger does not significantly reduce performance.

A TRNSYS model of the solar desiccant cooling process was developed to size key components and evaluate annual energy savings. The model incorporated three sub-models being:

1. *Desiccant cooling system sub-model*: In this sub-model, the desiccant wheel was modelled by interpolating desiccant wheel performance data obtained from the NovelAire Technologies Desiccant wheel simulation program (V2006 4.20) [4]. The indirect evaporative cooler was modelled with a secondary flow to primary flow ratio of 0.4 and an assumed effectiveness of 0.7. Fan power was set at 140 W when in summer cooling operation.

2. *Solar hot water system sub-model*: The hot water system comprised of 10m^2 of Rinnai flat plate solar collectors, an unheated 329 litre hot water storage tank and a backup Rinnai Infinity instantaneous gas heater (external to the storage tank). Thermal stratification in the hot water storage tank was modelled with twenty isothermal 'nodes'.

   The solar collector pump switched on during the day if the collector outlet temperature was greater than 10°C above the temperature at the bottom of the storage tank. The pump remained on until the collector outlet temperature dropped below the tank bottom temperature

   Gas boost was only used for heating potable hot water (drawn from the top of the tank) to 60°C. Australian Standard 4552 [6] was used to provide hot water energy demand profiles for use in the calculation of the energy required for potable hot water consumption. Gas was not used directly for space conditioning. However, because the desiccant cooling process removes thermal energy from the hot water storage tank, space conditioning may cause gas energy to be used indirectly to provide additional boost to the potable hot water.

3. *Building sub-model*: The building model is based on an Australian "5 star" house with two conditioned zones; an 80m^2 floor area combined kitchen/living space; an 80m^2 floor area bedroom space; and one non-conditioned zone for the ceiling space. Internal sensible and latent heat loads due to appliances, cooking, lighting and people were applied in each zone according to a daily schedule. This schedule is based on a two adult, two child household with a consistent daily occupancy and peak load periods in the morning and early evening.

The solar cooling system was designed to supply around one air change per hour (ACH) of fresh desiccant cooled air to the occupied space. This is thought to be sufficient to displace the natural air infiltration that would typically occur in Australian homes. This quantity of air gives around 1.6 kW of cooling capacity at design conditions. In addition to the solar desiccant cooling system, the house was assumed to have a back up mechanical air-conditioning system to ensure that comfort conditions could be maintained at all times.

The cooling control strategy aimed to: (i) minimise the duration and the required cooling output of the backup mechanical air conditioning system; and (ii) minimise parasitic electricity consumption from fans and pumps. The following strategy was implemented:

- If room temperature is greater than set point temperature, then solar cooling is activated
- If room temperature is more than 2.5°C greater than set point temperature, then the backup mechanical air-conditioner is activated and the direct evaporative cooler is turned off
- If room temperature is less than set point temperature, then the backup mechanical air-conditioner is switched off
- If room temperature is more than 1°C less than set point temperature, then solar cooling is switched off

The TRNSYS model was used to predict annual gas (hot water) and electricity (backup air-conditioner usage for space cooling and heating) energy consumption for the house in various Australian cities. Parasitic fan energy consumption by the solar system was also calculated. The resulting energy savings predicted for the house in Brisbane is illustrated in Figure 3.

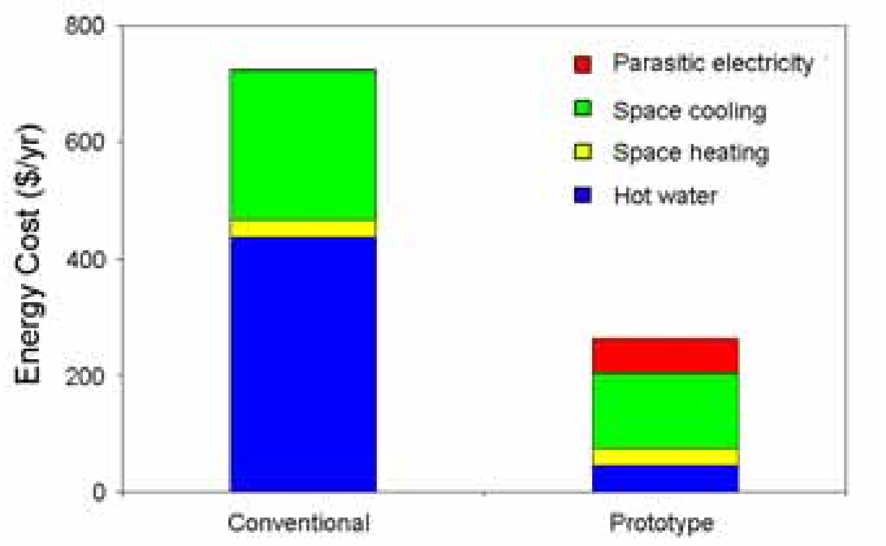

Figure 3: Comparison of Energy Cost Between (i) a Conventional Household (Gas Hot Water and Mechanical Air-conditioner) and (ii) a Household with the Solar Product in Brisbane (gas @ 6.4c/kWh, electricity @ 17.5c/kWh)

The model predicts a significant reduction in space cooling demand and a dramatic reduction in hot water consumption. Thermal energy costs in the household are reduced by over 50%.

3. Prototype Testing

A prototype of the proposed desiccant cooling system was constructed (Figure 4) and tested in the CSIRO Controlled Climate Test Facility at Newcastle, Australia (Figure 5).

Figure 4: Photograph of the CSIRO-Rinnai Prototype Desiccant Cooler under test in Newcastle.

Unfortunately, no commercially available indirect evaporative cooler was found that was suitably small for inclusion in the prototype. As a result, the indirect evaporative cooler was constructed by the combination of a cooling tower and a cooling coil.

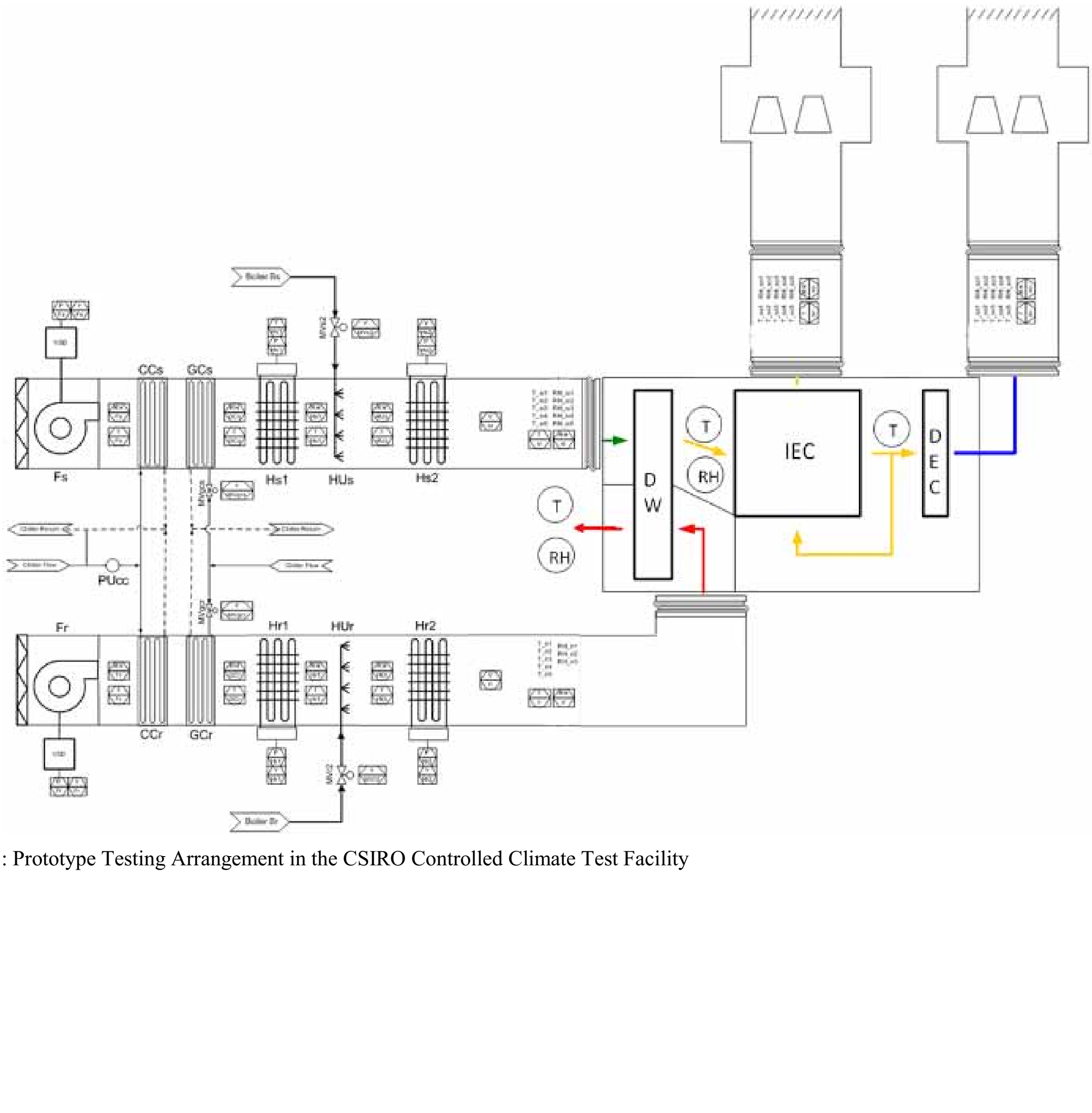

Figure 5: Prototype Testing Arrangement in the CSIRO Controlled Climate Test Facility

In this arrangement, dehumidified warm air is passed through the cooling coil. A fraction of the cooled air exiting the cooling coil (secondary air) is directed to the bottom of the cooling tower. Water leaving the bottom of the cooling tower is circulated through the cooing coil and passed to the top of the cooling tower where it is re-cooled by the secondary air stream.

The Controlled Climate Test Facility (CCTF) is described elsewhere [7]. The CCTF provides two air streams with tightly controlled temperature and humidity that are representative of: (i) ambient air to be dehumidified and (ii) solar heated air for regenerating the desiccant wheel. The CCTF also includes precision sensing equipment for measuring the temperature and humidity of entering and leaving air streams.

Initial testing of the prototype was performed under the following conditions:

- Ambient air intake at 29.5°C and 14.6 g/kg (Sydney summer design conditions)
- Regeneration air intake at 60°C and 14.6 g/kg
- Ambient air: Regeneration air flow ratio of 1:0.8
- Ambient air face velocity of 3 m/s
- Primary air (out): Secondary air flow ratio of 1:1

Tests were repeated with regeneration air temperatures of 50°C and 70°C.

The conditions of the cooled supply air to the building (leaving the desiccant cooling prototype) are illustrated in Figure 6.

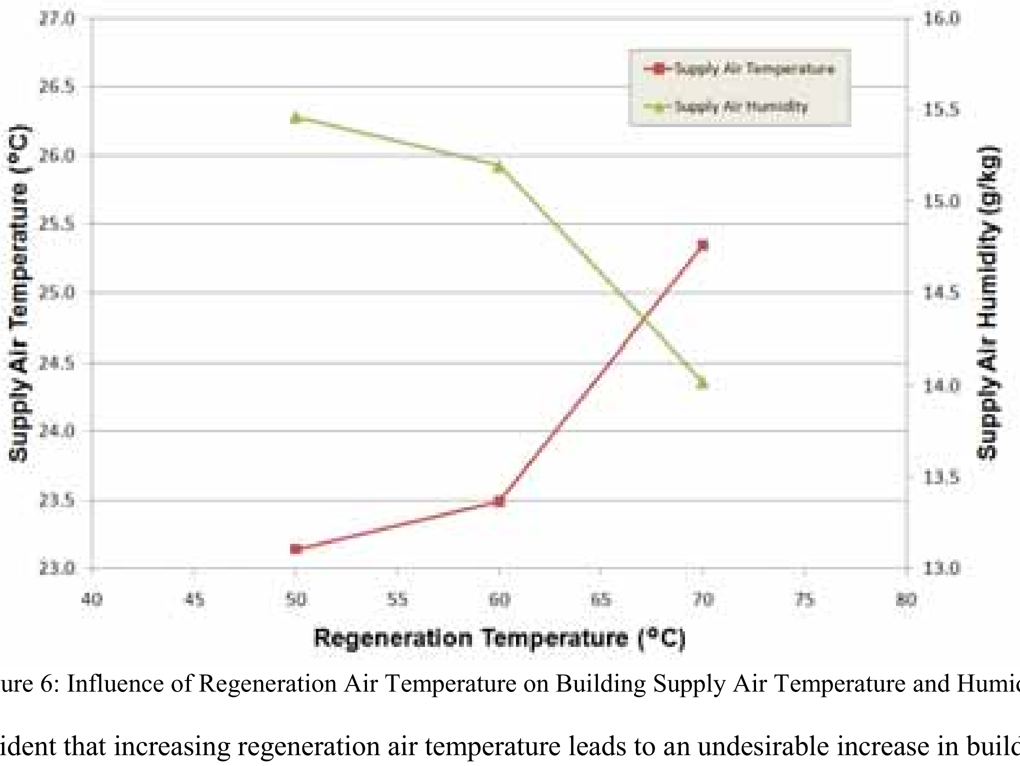

Figure 6: Influence of Regeneration Air Temperature on Building Supply Air Temperature and Humidity

It is evident that increasing regeneration air temperature leads to an undesirable increase in building supply air temperature, but achieves a reduction in supply air humidity.

The observed supply air temperature reduction by the desiccant cooling unit, of around 6°C, is less than expected. Further testing on the indirect evaporative cooler component of the system was conducted to determine whether: (i) further supply air temperature reductions would be possible; and (ii) if the TRNSYS model indirect evaporative cooler effectiveness assumption was valid.

For the new tests, the desiccant wheel was removed and the CCTF was set up to provide a simulated warm dehumidified air stream at 50°C and 10 g/kg. The direct evaporative cooler component was also removed, and tests were performed on the stand-alone indirect evaporative cooler with varying cooling water flowrates and with a varying fraction of the primary air stream being diverted to the cooling tower. Twenty tests were performed in all, with average error in the overall energy balance around the indirect evaporative cooler of +0.34% ± 1.13%.

Temperatures measured before and after the indirect evaporative cooler were used to calculate the effectiveness of the indirect evaporative cooler (Equation 1)

$$\varepsilon = \frac{T_{DB\,in} - T_{DB\,out}}{T_{DB\,in} - T_{WB\,out}} \qquad .....(1)$$

Where

ε is the heat exchange effectiveness of the indirect evaporative cooler unit

$T_{DB\ in}$ is the dry-bulb temperature of air entering the indirect evaporative cooler

$T_{DB\ out}$ is the dry-bulb temperature of cooled air leaving the indirect evaporative cooler

$T_{WB\ out}$ is the wet-bulb temperature of cooled air leaving the indirect evaporative cooler (condition of air supplied to the bottom of the cooling tower)

The influence of cooling water circulation rate and secondary air fraction on the effectiveness of the indirect evaporative cooler is illustrated in Figure 7.

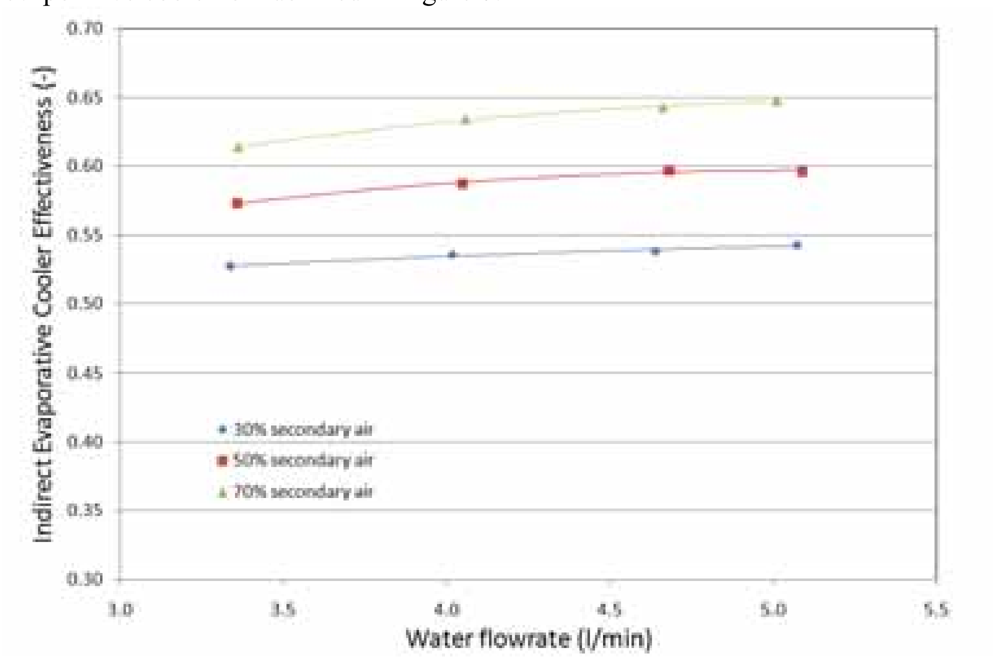

Figure 7: The influence of Cooling Water Flowrate and Secondary Air Fraction on Indirect Evaporative Cooler Effectiveness.

Water circulation rate had only a small effect on the effectiveness of the indirect evaporative cooler. While increasing the fraction of cooled secondary air diverted to the cooling tower increases the effectiveness of the indirect evaporative cooler, this is obtained at the expense of reduced air flowrate that can be supplied to the building. Optimal cooling capacity would tend to favour low secondary air fraction which leads to an indirect evaporative cooler effectiveness less than 55%. This is considerably less than the assumed 70% effectiveness in the TRNSYS model, and which is achieved by commercially available indirect evaporative coolers.

4. Conclusion

Residential air-conditioning demand is growing rapidly in Australia, contributing to increased greenhouse gas emissions and peak demand for electricity infrastructure. CSIRO and Rinnai have developed a new 3-in-1 solar product designed to produce hot water, supply winter space heating; and provide summer space cooling. This product is expected to provide a more sustainable alternative to conventional fossil fuel derived energy sources. The cooling component of the system uses desiccant cooling technology, which has a number of advantages over alternative thermally activated cooling technologies in residential applications.

A TRNSYS model of a $160m^2$ house was developed, incorporating a one air-change per hour desiccant cooler and a $10m^2$ flat plate solar hot water system. Annual energy savings, from reduced usage of the backup conventional air conditioner and reduced usage of backup hot water heating, are predicted to reduce household energy cost by more than 50%.

A prototype of the product was constructed and tested under controlled conditions in the CSIRO Controlled Climate Test Facility (CCTF). Initial testing of the desiccant cooling component found that the desiccant cooling system reduces building supply air temperature by around 6°C under design summer conditions. Further testing of the indirect evaporative cooler component found that, at low secondary air flowrates, the effectiveness of the indirect evaporative cooler was less than 55%. Further research is required to increase this to around 70%.

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References

[1] A. Preisler, "Reduction of Costs of Solar Cooling System" ROCOCO Publishable Report, EU 6th Framework Project nº TREN/05/FP6EN/SO7.54855/020094, June 2008

[2] M. Beccali, P. Finocchiaro, B. Nocke and S. Gioria, "Solar Desiccant Cooling AHU Coupled with Chilled Ceiling: Description of a New Installation at Dream in Palermo", Proc. 2nd Int. Conf. On Solar Air-Conditioning, Tarragona, Spain, October, 2007, 402-407

[3] Y.J. Dai, D. La, Y. Li, Z.X. Jiang, T.S. Ge and R.Z. Wang, "An Energy Efficient Solar Driven Two-Stage Rotary Desicaant Cooling System: Experimental and Case Study", Proc. 3rd Int. Conf. On Solar Air-Conditioning, Palermo, Sicily, September, 2009, 572-577

[4] NovelAire desiccant simulation program v4.20. 2006 Available from: http://www.novelaire.com/.

[5] Australian Building Codes Board, "Protocol for house energy rating software". 2006.

[6] AS 4552-2005 Gas fired water heaters for hot water supply and/or central heating. 2005, Standards Australia: Sydney. Australia

[7] D. Rossington, S. White, A. Weigand, R. Sire, R. Reece and P. Kohlenbach, "Comparison of Silica Gel and Zeolite Desiccant Wheel Performance", Proc. 3rd Int. Conf. On Solar Air-Conditioning, Palermo, Sicily, September, 2009, 230-235