A COMBINED HEAT AND POWER SYSTEM FOR BUILDINGS DRIVEN BY SOLAR ENERGY AND GAS

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ABSTRACT

A novel hybrid solar/gas system intended to provide cooling/heating and electricity generation for buildings was developed. The system is based on the combination of an ejector heat pump cycle with a Rankine cycle. It is driven by solar energy and supplemented by a gas burner. The system also uses an environmentally-friendly refrigerant to have minimal impact on the environment. Results of system computer modelling, prototype tests and economic analysis are reported. The system was judged to be viable and reliable. Technical improvements still have to be achieved to improve system economics.

KEYWORDS

Cooling, Power generation, Ejector heat pump, Solar energy

1. INTRODUCTION

Existing large-scale plants for power generation are usually located far away from centres of population. This prevents the efficient utilisation of the waste heat produced. Moreover, current technology limits these power stations to a maximum efficiency of about 40%, which, after the transportation of electricity through the grid, is reduced to about 30%. This means that vast quantities of fossil fuels are burnt releasing unwanted pollutants (CO_2, NO_x, …) into the atmosphere.

Use of renewable solar energy in conjunction with conventional energy sources to meet electricity, heating and cooling requirements of buildings, would reduce pollutant emissions and offer savings. Solar energy has been used to generate electricity and several studies have investigated the use of power from photovoltaic systems for heating, ventilation and air-conditioning building plants. Unfortunately, photovoltaic technology has low efficiency and high capital cost. Solar energy could also be used to generate electricity using a Rankine cycle, in which a turbine or an engine is employed to convert thermal energy into mechanical energy.

The system presented in this paper is a novel hybrid solar/gas system, [1]. It can provide electricity, heating and cooling for buildings. It is based on the combination of an ejector cycle heat pump with a turbine/generator group and is powered by solar collectors supplemented by a gas burner, for periods of low solar radiation. The system employs an "ozone-friendly" refrigerant: n-pentane.

Figure 1 schematically represents the combined ejector cycle and power cycle. Heat is supplied to the boiler by combining solar collectors and a gas burner.

Results of numerical simulation and prototype experiment will be presented, namely concerning system performance, costs and emissions.

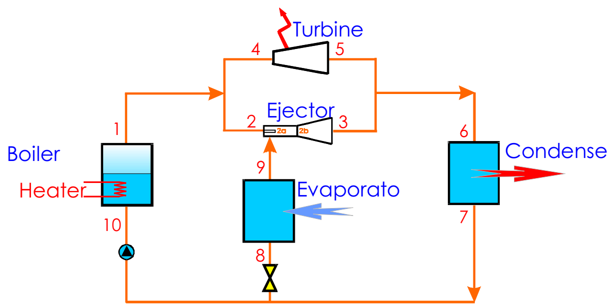

Figure 1 – Representation of the combined ejector/Rankine cycle.

2. COMPUTER MODELLING

A computer model was developed to simulate system potential performance. The model used as inputs the electricity generated, cooling effect, evaporator, condenser and boiler temperatures. Calculated values were energy needed in the boiler and system coefficient of performance (COP). Ejector performance was modeled through the use of isentropic efficiencies for each of the three zones: nozzle, entrainment and diffuser, [2]. Turbo-generator efficiencies were also fixed. Results for 3 different refrigerants and generator (boiler) temperatures are shown in Figure 2. System COP is defined as useful energy (cooling plus electrical power) divided by energy input in the boiler. As can be seen, n-pentane leads to the best results, with a COP between 0.3 and 0.5, depending on the boiler temperature. It was also found that system performance is very sensitive to turbine efficiency, thus pointing to the importance of this component.

To quantify solar energy contribution to energy input (boiler), simulations were carried out on an hourly basis, using climatic data for Portugal and UK and performance data for evacuated type solar collectors. It was found that a collector area of 20 m^2 in Lisbon (Portugal) could lead to a solar fraction of 0.3. Solar fraction means the fraction of energy needs that are met by solar energy. By doubling the collector area the solar fraction could increase to 0.5.

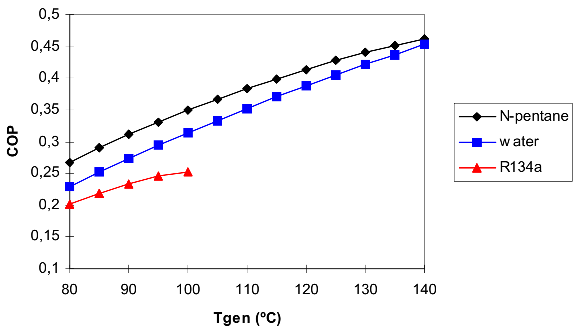

Figure 2 – Comparison of COP results for different refrigerants, for a turbine efficiency of 90%, evaporation temperature of 15ºC and condensation temperature of 35ºC.

3. PROTOTYPES AND TEST RESULTS

A number of refrigerants were investigated as potential working fluids for the system. A test rig was assembled for evaluating the performance of different refrigerants. It consisted of a boiler, a turbo-generator, a condenser and a pump. After experiment, and also taking into account simulation results, n-pentane was chosen as working fluid for the system prototypes. This refrigerant is not harmful to the environment

Two prototypes were assembled. One with a nominal cooling capacity of 2 kW and the other with 5 kW. The turbo-generator had a nominal power output of 1.5 kW. The miniature water cooled turbo-generator can be seen in Figure 3. It was bought from an UK manufacturer.

One prototype was tested in Loughborough (UK), connected to a 20 m^2 solar collector array, while the other one was tested in Porto (Portugal), using a gas burner. Figure 4 shows a view of the test facility located in Porto, where a test cell was used as cooling space.

Tests confirmed system reliability. Results were an average cooling cycle COP around 0.3 and electricity production efficiency between 3 and 4%, for an ambient temperature of about 20ºC. These values correspond to a boiler temperature of 95ºC, and could be improved by using a higher temperature. Electricity consumption for pumps/fans was negligible.

Turbine efficiency was also measured, and the value obtained was 28%, which is mainly due to friction losses and energy dissipation to cooling water. In order to increase significantly electricity production efficiency, a new turbine unit should be developed in the future.

Figure 3 – Miniature turbo-generator.

Figure 4 – View of prototype tested in Porto.

4. COST AND EMISSIONS ANALYSIS

A cost analysis was made, taking into account initial and operating costs. System projected initial cost is about 8500 Euro, plus solar collector cost, which depends on collector area (climate). System and economic modeling was applied to 3 potential sites, with different climatic conditions: Lisbon (Portugal), Loughborough (UK) and Darwin (Australia). Darwin was considered since it has a more favourable climate and Australia has a history of development and use of solar energy for water and space heating.

It was considered that the system could provide cooling in the cooling season and space or water heating during the rest of the year. As an example, Figure 5 shows energy output capability of the system, for Lisbon. Note that the system was considered to provide cooling in the cooling season, space heating in winter, water heating all year round and electricity generation in spring, summer and winter. This matches the profile for the system better than trying to maintain electricity generation all year round.

The methodology for calculating the overall cost – in euro/kWh – for each site was based on an accounting of the energy required to satisfy the set demands and an estimation of the capital costs and running costs for each case. A cost figure was defined as:

$$\text{cost figure} = \frac{\text{capital} + \text{running} + \text{maintenance}}{\text{energy delivered / year} * \text{number years}} \quad (1)$$

Table 1 presents cost figures for the combined system and for a conventional system using a vapour compression heat pump and electricity from the grid. The cost based on cooling and electricity generation only is quite high, due to the low usage of the system. When considered as a system delivering cooling, electricity and space/water heating the economics improve considerably.

Results show that nearly competitive costs can be achieved for the system in areas with a large demand for generation and cooling. This was the case for Darwin, with average cost figures as low as 0.154 euro/kWh for cooling and electricity generation coming down to a figure of 0.097 euro/kWh if there is a demand for water heating.
The costs for Loughborough and Lisbon are higher due to a smaller cooling season. Note that the use of waste heat to drive the combined system, instead of gas or solar energy, would further reduce cost figures to below conventional system costs.
To assess the impact of the combined system on the environment, an emissions analysis was carried out. It was carried out for each of the sites, comparing the CO_2 emissions from the solar/gas system with an upper and lower bound using conventional methods. The lower bound was for a combined cycle gas turbine and the higher bound was for generation of electricity by a coal fired power station. In all cases with the solar/gas hybrid system using waste heat for space or water heating, the average CO_2 emissions are towards the lower boundary of conventional systems. This shows that the potential of the combined system for saving emissions is high when compared to coal fired production and is as good as a combined cycle gas turbine providing electricity and with a natural gas burner for providing heating. The figures for all three sites are given in Table 2.

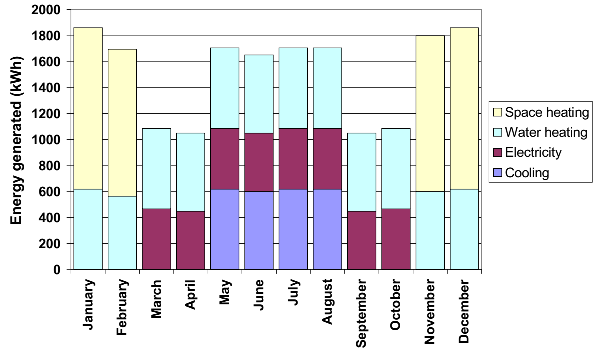

Figure 5 – Energy generated and end use for Lisbon.

Table 1 – Cost figures (euro/kWh) for 3 sites.

	SYSTEM	PERIOD	10 YEARS	15 YEARS	20 YEARS
LISBON (PORTUGAL)	conventional system	Cooling/electricity	0.282	0.247	0.230
		Cooling/electricity and heating	0.124	0.110	0.103
	combined system	Cooling/electricity	0.462	0.352	0.297
		Cooling/electricity and heating	0.166	0.126	0.107
DARWIN (AUSTRALIA)	conventional system	Cooling/electricity	0.134	0.117	0.109
		Cooling/electricity and heating	0.102	0.089	0.084
	combined system	Cooling/electricity	0.230	0.179	0.154
		Cooling/electricity and heating	0.146	0.114	0.097
LOUGHBOR. (UK)	conventional system	Cooling/electricity	0.365	0.269	0.285
		Cooling/electricity and heating	0.094	0.082	0.077
	combined system	Cooling/electricity	0.994	0.742	0.615
		Cooling/electricity and heating	0.188	0.140	0.116

Table 2 – Comparison of CO2 emissions from conventional generation and the combined solar/gas system.

System	Lisbon	Darwin	Loughborough
Conventional (Upper)	430 g/kWh	511 g/kWh	334 g/kWh
Conventional (Lower)	233 g/kWh	226 g/kWh	222 g/kWh
Solar/gas system	223 g/kWh	275 g/kWh	235 g/kWh

5. CONCLUSIONS

Two system prototype units were successfully built and tested. Cooling capacities up to 5 kW and electrical output up to 1.5 kW were achieved.

The main technical improvements to be achieved concern the turbo-generator and the ejector components. Electricity generation efficiency can be increased by modifying the turbo-generator and also by increasing boiler pressure (temperature). To improve the efficiency of the cooling process, ejector development will continue.

According to the economic analysis, nearly competitive costs for the system can be achieved if the generated waste heat is used for water or space heating. System competitiveness is higher in hotter climates.

At the present state of development the system is very interesting from the point of view of power generation decentralisation, reduction of fossil fuel consumption and reduction of harmful emissions to the environment. These will be particularly significant if waste heat is used as a complement for solar energy to drive the system.

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