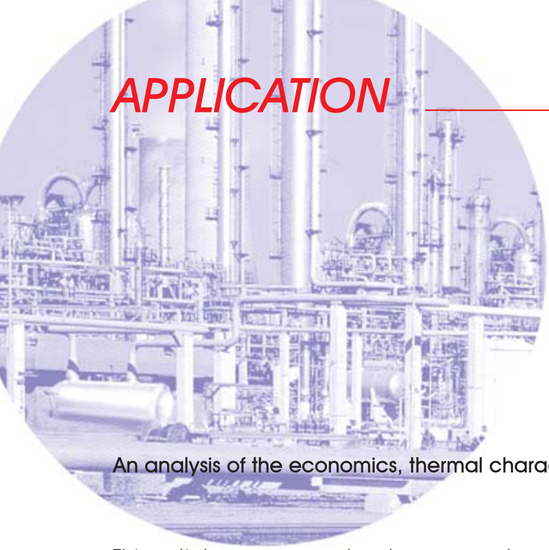

Performance of heat pumps in South Africa

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An analysis of the economics, thermal characteristics and development of heat pump water heaters in South Africa.

This article compares heat pump water heaters with a solar water heater and a conventional electrical resistance heater based on energy consumption. The conclusions suggest that the design and control should be specific for the mild South African climate and that large-scale implementation of heat pump water heaters can be used as an efficient technology to reduce energy consumption.

Electricity consumption increased by about 25% between 2000 and 2007 due to rapid economic growth in the past decade. South African generation capacity, however, was constant at about 40 GW. In 2008, the power supply could not meet the demand, causing many parts of the country to experience black-outs.

Coal is still the main source used for electricity generation. However, the burning of coal has a significant effect on the environment, especially in terms of CO_2 emission. Under "business-as-usual" conditions, the requirement is to reduce total energy consumption by 12%, with a 10% reduction from the residential sector by 2015.

The largest energy consumer in domestic homes is the electric water heater (geyser).

The existing water heating methods are electrical resistance water heaters (ERWHs); heat pump water heaters (HPWHs); solar water heaters (SWHs); gas heating; wood heating; paraffin and others. In South Africa, 81,2 and 54,3% of households use electricity to heat water in urban and rural areas respectively. The average hot water consumption in summer among low, medium and high incomes are 20, 50 and 70 l/day respectively, and in winter is 30, 70 and 120 l/day respectively. To achieve a reduction in the domestic sector, Eskom introduced integrated demand management (IDM). For residential water heating, Eskom's IDM promoted two energy-efficient technologies with rebates – SWHs and HPWHs. In this article, the comparison of HPWHs with SWHs and conventional ERWHs will be compared in terms of energy use. The energy efficiency of a heat pump is defined by the coefficient of performance (*COP*) which is given by:

$$COP = \frac{useful\ heat\ output}{power\ input}$$

$$= \frac{Q_{con}}{W_{com}}$$

where Q_{con} is the heat rejected from the condenser W_{com} is the mechanical work performed by the compressor. On average, the COP of a HPWH is between 2 and 5,5 with an average value of 3. Therefore, 67% of the electrical energy consumption can be saved compared to an ERWH. In most South African households, 30 – 50% of the electricity bill is generated by water heating, which means an HPWH can save about 25% of the total residential electricity consumption. Eskom's IDM rebate programme for HPWHs can reduce the initial cost by 30 – 50%.

Heat pump water heater

Heat pumps (HPs) can generally be classified into air source heat pumps (ASHPs), ground source heat pumps (GSHPs) and chemical heat pumps (CHPs), or as electrically-driven heat pumps and gas/fuel engine driven heat pumps.

The main components for all types of vapour compression heat pumps are an evaporator, condenser, compressor and an expansion device. The basic operating principles remain the same.

In the South African market, most HPWHs are air source electrically driven heat pump water heaters. The principle of an HP system is the same as that of an air conditioning system, which uses the change of state of refrigerant to absorb heat from the lower temperature source and releases more heat to the highertemperature source.

Methodology

Energy consumption analysis

The thermal demand for residential water heating $E_{th,d}$ is represented as:

$$E_{th,d} = \sum_i W_i \cdot P_i \cdot c_p \cdot \Delta T \cdot n_{pi}$$

where:

W_i is the hot water requirement per person per year in a dwelling.

P_i is the number of persons.

ΔT is the temperature difference between cold water inlet and hot water outlet.

c_p is the specific heat of water which is 4,19 kJ/(kg K).

η_{pi} is the efficiency of the water heating device.

The average annual values for W_i are 9125 l per person per year; 21 900 l per person per year; 34 675 l per person per year for low, medium and high incomes respectively.

The average water inlet temperatures are 9 and 19°C in winter and summer in Gauteng province (14°C average). The efficiency of hot water storage is taken as 0,9. Energy efficiency has a significant effect on electrical consumption for different water heating methods. The energy efficiency for an ERWH is about 80%. The annual electricity consumption is:

$$E_{ERWH} = \frac{E_{th,d}}{0,8x3600\ x\ 1000}(kWh)$$

The average COP for a HPWH is 3, the annual electricity consumption is:

$$E_{HPWH} = \frac{E_{th,d}}{0,8\ x\ 3600\ x\ 1000}(kWh)$$

There are more than 320 sunny days a year and the irradiation is around 240 W/m^2 in South Africa. The advantage of solar technology is clear. However, a SWH still needs backup power during nights and on cloudy days. SWH systems use conventional electrical resistance as backups. The assumed percentage of required backup is 20%, therefore, the annual electricity consumption of a SWH is:

$$E_{SWH} = \frac{E_{th,d}}{0,8\ x\ 3600\ x\ 1000} x\ 20\%\ (kWh)$$

The theoretical annual electricity consumptions of ERWHs, HPWHs and SWHs show significant energy savings from HPWHs and SWHs. A SWH also provides a higher energy saving fraction than an HPWH because a HPWH system always needs electrical power to drive the refrigeration cycle, while an SWH system only needs the backup electricity power when there is little or no solar energy or when the solar energy is not enough. The graph also shows that there is much more potential to save energy by high-income households than by others. The more occupants in the household, the more energy can be saved.

Thermal performance of HPWHs

For an HPWH, the energy efficiency can be improved by reducing power input or by reducing heat loss. According to the principle of the first law of thermodynamics, a mathematical model of the evaporator heat load can be:

$$Q_e = m_r(h_1 - h_4)$$

where:

m_r is the mass flow rate in kg/h.

h is the enthalpy in kJ/kg.

If there are no losses during the heat transfer process, equation can also be:

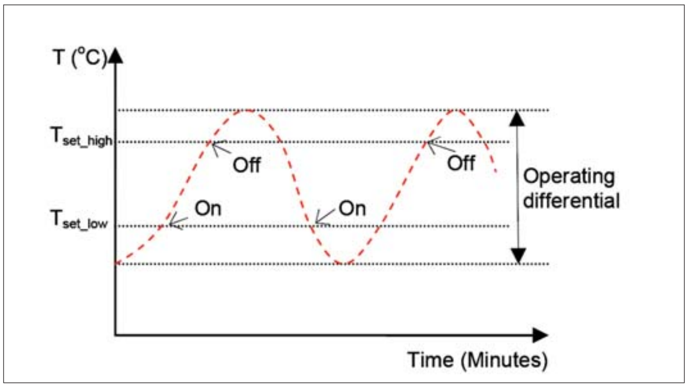

Fig. 1: On/off control of setting temperatures vs time.

$$Q_e = \Delta t \cdot h_c A_e (T_a - T_e)$$

where:

Δt is the operation period in seconds.

h_c is the convection heat transfer coefficient in W/(m^2°C).

A_e is the evaporator surface area in m^2.

T_a is the ambient temperature in °K.

T_e is the evaporator temperature in °K.

Theoretically, the total heat rejected of a condenser is the sum of heat load at the evaporator and power input at the compressor. Therefore, the equation is:

$$COP = \frac{Q_e + W_{com}}{W_{com}} = \frac{\Delta t \cdot h_c A_e (T_a - T_e) + W_{com}}{W_{com}}$$

This equation indicates that the increase of T_a or A_e will improve the *COP* if other parameters are constant. Due to its mild climatic conditions. South African HPs can achieve a higher *COP*. The size of the evaporator area, the piping of the system, the throttling device configuration etc. also have a significant effect on *COP*, and these factors increase the performance of HPWHs.

Development and future trends in HPWHs

Recent progress in HPWHs

Currently, most HPWH products are imported from other countries and are not designed to South African specifications. R134a, R407 and R417a are used as common refrigerants in HPWHs. They are used to replace R22, but they are not as stable as expected. The heating capacity is around 3 kW. The operation control methods are on/off control and timer control.

On/off control is a common method for most thermal products. The basic principle is shown in Fig. 1. There are two set temperatures, T_{set_high} and T_{set_low}. The required temperature is the average value of T_{set_high} and T_{set_low}. When the water temperature in the storage tank achieves T_{set_high}, the system stops operating. When the water temperature in the storage tank decreases to T_{set_low} the system starts to run.

Future trends in HPWHs

- Both HPWHs and SWHs can save energy during water heating. The application of solar assisted HPWHs offers more savings potential. Solar assisted HPWH systems are more suitable for large-scale water heating.
- The use of compounds such as carbon dioxide and nitrogen oxides is encouraged as "green" refrigerants to replace conventional ones.
- To improve refrigeration cycles by using engine driven heat pumps and multiple-stage operations. However, the cost of multiple-stage HPs will be much greater than that of single-stage HPs. Multiple-stage HPs are suitable for large-scale users such as schools or hospitals.
- The design specifications must be applied in accordance with South Africa's climate conditions.
- Techniques of compressor capacity control can be employed by varying the refrigerant flow-rate in the cycle. Capacity control methods commonly applied are on/off control, evaporator temperature control adjusted by fan speed, clearance volume control and variable speed drive (VSD) control. VSD control is the most energy efficient method. While the water is being kept warm, the application of a VSD to reduce compressor speed will save some energy.

Conclusions

The advantages of HPWHs are outstanding, but a lot of work and research must be done to expand this market and improve their performance.

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