Heat Pump for Heating Water for Domestic Purposes Using a Varying Speed Compressor Control

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Abstract: A computer simulation is developed to study the energy efficiency of a heat pump with a controlled variable speed compressor to heat bath water in a residential building. The usage of electric energy to heat water in Brazil will be discussed to give the context of the proposed set. Scroll compressor is chosen as the variable speed compressor, a heat pump model is used and also water distribution models that consider the local heat losses. A PID controller is used and different techniques of references are considered to determine the reservoir water temperature. Results are discussed and compared to traditional Joule effect water heating.

Keywords: Compressors, PID control, Heat Pump, Hot water, Greenhouse effect.

1. INTRODUCTION

Although Brazil is a tropical country the use of hot water in bath is very common comfort feature. The most used method to heat water in Brazil is the electric shower, which employs the Joule effect. This method is very simple, cheap to install but thermodynamically irreversible, and so highly expensive in terms of energy. From the point of view of the power plant and distribution systems, other problem related to the electric shower is the concentration of the consumption of electric energy at specific times in the day. The present study is focused on the Southeast region, the most industrialized region of the country, where the electric shower is used by more than 80% of the residences studied by SINPHA (2007). During the day the electric shower is responsible for a high consumption during early morning (5a.m - 9a.m) and mainly during beginning of the evening (18a.m – 21a.m). Usage of solar heating is still modest, possibly because of the initial coasts, but it is increasing steadily in one-family houses. However, it is not an appropriate solution for high buildings, which lack enough roof area. The present work focuses on an alternative heating method provided by heat pump with a controlled speed scroll compressor and a hot water reservoir. The initial cost of the system would be shared by several residents and became economically attractive. The advantages of this method are the low consumption of electric energy compared to the traditional Joule effect method and the distribution of energy consumption thought out the day. This work focuses on a computer simulation of the water temperature control, based on an estimated water consumption model, a heat pump with controlled scroll compressor model and a heat losses model considering estimated environment temperatures.

2. REVIEW

2.1 Heat Pump use and the greenhouse effect

Heat pumps are CO_2 free equipments as soon as the electric energy is obtained by CO_2 free processes, such as nuclear, hydroelectric, eolic and others. Even in the cases in which the electric energy comes from a modern natural Gas power plant, with 57-58% efficiency, a heat pump with a 3.5 COP would have heat efficiency using heat pump of approximately 200% compared to the direct burn of the gas. (Dornes et al., 2003)

2.2 Variable Speed Compressor

Although there are many ways to control a heat pump (Quereshi et al., 1995) they have different energy consumption varying on the work requests. For a 50% of charge, the traditional on/off control method consumes 65% of full load power, and discharge gas bypass consumes 90%. Using varying speed compressor consume reduces to 55%. So it is clear that the varying speed compressor is a mechanism that has almost no losses, which is fundamental because the present system is supposed to work on very variable work conditions during the day. The scroll compressor was chosen for the present work because it satisfies some conditions on work frequency, lubrication, suction valves tension and an almost linear speed/efficiency relation.

2.3 Scroll compressor

Scroll compressors are orbital motion, positive-displacement machines that compress with two interfitting, spiral-shaped scroll members (ASHRAE, 2001). Capacities range from 3 to 50 kW. Typical operating frequency varies between 15 and 150 Hz. The capacity provided by the machine is nearly directly proportional to its running frequency. The variable-speed scroll compressor uses an inverter drive to convert a fixed frequency alternating current into one with adjustable voltage and frequency, which allows the variation of the rotating speed of the compressor motor.

3. MATHEMATIC MODEL

3.1 Heat pump with variable speed Scroll compressor

The temperature evolution of the hot water in the reservoir and circuitry is determined by the first law of thermodynamics.

$$\rho\, V\, c \frac{dT_r}{dt} = \dot{m}_h\, c\left(T_{env} - T_r\right) + \dot{m}_b\, c\left(T_{ret} - T_r\right) + \dot{Q}_c - \dot{Q}_r \qquad (1)$$

Where ρ is the specific mass of water, V is the volume of the hot water reservoir and tubing, c is the specific heat of water, T_r is the temperature of the reservoir, T_{env} is the environmental temperature, T_{ret} is the temperature of hot water returning to the reservoir, m_h is the mass of hot water that goes to the user, m_b is the mass of water that comes back to the reservoir after the circulation, Q_c is the heat flux from condenser and Q_r is the heat loss from the heat pump the reservoir. Equation 1 is solved by means of a simple Euler time wise integration. Within each time step, heat losses are computed explicitly and the off-design heat pump model is run to determine the water heating rate.

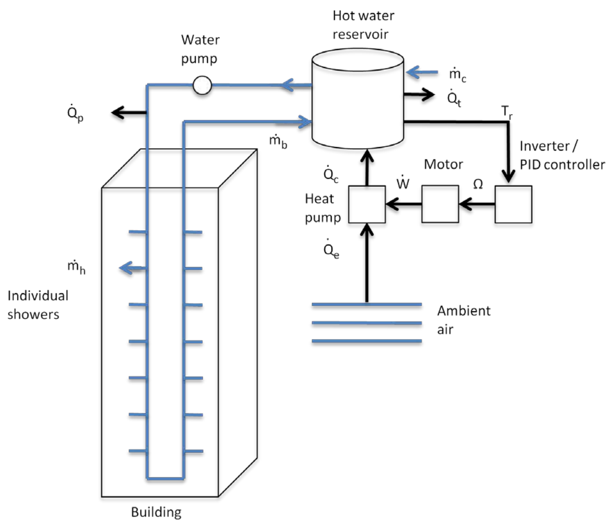

Fig.1: Hot water distribution, Heat Pump and Control scheme.

The heat pump model uses the steady-state mass and energy-conservation principles for each component of the heat pump (evaporator, condenser, expansion valve and compressor) as a control volume, together with heat transfer relations for the heat exchangers, and empirical relations for the compressor isentropic and volumetric efficiencies. The thermodynamic properties of the fluid R-134-a are evaluated according to the method of Helmoltz free energy. This model is capable of sensibly representing the heat pump performance in view of the reservoir and environment temperatures as well as the motor frequency. For algebraic details of the heat pump model, the reader is referred to Figueiredo et al. 2002, except for the compressor, since the reciprocating volumetric η_{vol} and adiabatic efficiencies η_{ad} models used there are replaced by the scroll characteristics expressed by (2) and (3).:

$$\eta_{ad} = 0.855 - 0.045 \frac{p_{out}}{p_{in}} \qquad (2)$$

$$\eta_{vol} = 1.08 - 0.04 \frac{p_{out}}{p_{in}} \qquad (3)$$

Where p_{out} is the pressure in the outlet of the compressor and p_{in} the pressure in the inlet of the compressor.

The steady state hypothesis for the heat pump model is justified in this modelling considering the mechanical and thermal response of the heat pump to be much quicker than the daily oscillations of the reservoir temperature. Summing up, the model is reduced to a sparse set a 30 algebraic equations and correspondent variables. It is solved by a variation of Newton Raphson method with numerically computed differentials, preceded by a minimization of the number of effective variables that reduces the matrix problem from dimension 30 to 7 only.

The modified Newton-Raphson procedure is used in two modes: design mode and off-design mode. For the design mode, we depart from estimated hot water demand and specified environment temperatures. Assuming also representative, moderate values for the evaporator and condenser temperature differences, the model equations can determine the necessary heat transfer global coefficient multiplied by the heat transfer area of the evaporator and condenser, as well as the compressor volumetric rate. In the present case, these design parameters are: UA_{evap} = 599.690 W/K, UA_{cond} = 541.650 W/K, υ_{scr} = 0,000045 m^3.

3.2 Building, water consumption and heat loses

The hot water reservoir is a cylinder made of cement and isolated. Heat losses to the air Q_r are assumed to occur on the side, on the top and on the bottom faces. Therefore (5)

$$Q_r = \frac{T_{env} - T_r}{\left(\dfrac{e_c}{k_c 2\pi r^2} + \dfrac{e_{iso}}{k_{iso} 2\pi r^2}\right)} + \frac{T_{env} - T_r}{\left(\dfrac{\log\left(\dfrac{e_c + r}{r}\right)}{(2\pi k_c H_t)} + \dfrac{\log\left(\dfrac{e_{iso} + e_c + r}{e_c + r}\right)}{(2\pi k_{iso} H_t)}\right)} \qquad (5)$$

Where e_c is the thickness of the cement wall, e_{iso} is the thickness of insulating material, k_c and k_{iso} are the coefficients of heat transfer of the cement and the insulating material respectively, r is the inner radius of the cylindrical reservoir and H is the reservoir height.

Heat losses though the pipes Q_p are given by (6)