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Development And Validation Of A Simulation Model For Heat Pump Water Heater

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ABSTRACT: A simulation model for heat pump water heater (HPWH) was developed and validated in this paper. The basic components of the HPWH, such as compressor, condenser, and evaporator, were simulated. The key point of this simulation model is using characteristic functions to describe the volumetric and isentropic efficiency of the compressor from three sets of experimental data corresponding to three sets of operating conditions. Using a small amount of experimental data in forming these characteristic functions helps save time and costs. To validate the simulation model, experiments were carried out with operating an actual HPWH. The maximum difference in the coefficient of performance (COP) between the simulation results and experimental results is 5,0%. By the results, it was found that the simulation results agreed well with the experimental results. Finally, the effects of the inlet water temperature and ambient temperature on the COP of the HPWH were studied.

KEYWORDS: simulation, heat pump, isentropic efficiency, volumetric efficiency, COP.

INTRODUCTION

The process of water heating consumes enormous amounts of energy. In households, it can account for up to 40% of the total energy used [1][2]. In commercial buildings, this energy is the fourth largest energy after heating, air conditioning, and lighting. Hot water is also used in many applications such as food processing, laundry workshops, hospitals, hotels, swimming pools, etc [3][4]. Besides, hot water is used in many other special cases, for example, to ensure the optimum growth temperature of fish in aquaponics systems [5][6].

The most popular method of heating water today is to use resistors or fossil fuels. However, these methods' disadvantages are low energy efficiency and high emissions that adversely affect the environment [3]. To save energy, one of the practical method is applying HPWH. Using HPWH, power consumption is only about 25% to 50% compared to the resistance method [1][7]. HPWH is widely used around the world, increasing by about 10% per year. Although HPWH uses less energy than a resistor, its power consumption is still enormous. Therefore, it is important to manufacture and operate an HPWH system that is more energy efficient. HPWH simulation is one of the effective methods to perform this problem [8 - 10].

Many studies of HPWH have been done including structure [8][11], numerical simulation [10 - 13], thermodynamics and working fluids [14 - 18], operation controlling [14][19][20], etc. The studies contribute to expanding the application of HPWH in practice. In simulation studies, two important compressor performance parameters, volumetric efficiency and isentropic efficiency, are often regarded as a function of the pressure ratio. In fact, they depend on both evaporation and condensation pressures. In this study, in order to increase the accuracy of the simulation model, the performance functions were created as functions of the two independent variables mentioned above. The simulation model has been validated by an actual HPWH. Simulation results are in good agreement with the experimental data indicates that the HPWH simulation is high precision. The HPWH simulation model is used to study the COP of HPWH under different operating conditions [21].

WORKING PRINCIPLE AND SIMULATION MODEL

HPWH uses electricity to move heat from the air to hot water instead of generating heat directly. Therefore, it can be two to four times more energy-efficient than typical electric resistance water heaters. The typical HPWH used in this study is shown in Fig. 1. It has four major components: a compressor, a condenser, an expansion device, and an evaporator [17]. They are connected in a closed-loop so that the refrigerant is continuously circulated. Typically, the HPWH will be connected directly to a hot water tank, which is used to store heat energy.

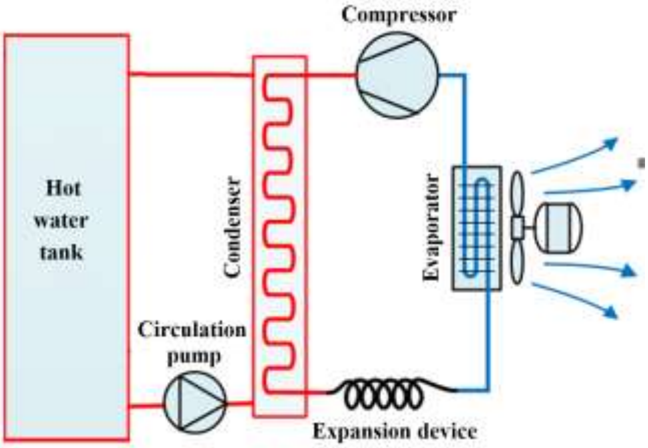

Figure 1. Air source heat pump water heater

The thermodynamic cycle of HPWH is shown in Fig. 2. The processes of the cycle include compression (1-2), condensation (2-3), expansion (3-4), and evaporation (4-1). Typically, condensation and evaporation are isobaric processes. In the expansion process, enthalpy is constant. Theoretically, the compression process is adiabatic. In order to increase the accuracy of the calculation, the actual compression process is used with the performance curve (1-2r) and is determined through isentropic efficiency, defined by equation (1).

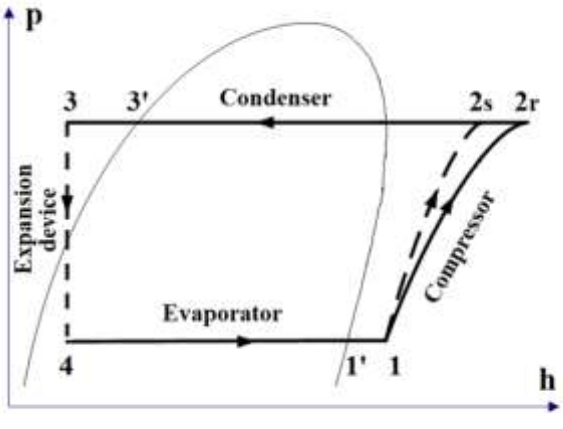

Figure 2. p-h diagram of the heat pump water heater

$$\eta_s = \frac{h_{2s} - h_1}{h_{2r} - h_1} \quad (1)$$

To study HPWH's operation under different conditions, all major components of the HPWH, such as compressor, condenser, and evaporator, were simulated.

Compressor

The compressor is the most important device in the HPWH because it uses the most energy and contains complex parts. There are two key parameters in the compressor simulation model. They are compressor mass flow rate (m_r) and electrical power (N_{el}), which are given by equations (2), (3) respectively.

$$m_r = \frac{\eta_v V_s n}{v_1} \tag{2}$$

$$N_{el} = \frac{m_r (h_{2s} - h_1)}{\eta_s \eta_{me} \eta_{el}} \tag{3}$$

Where η_{me} is mechanical efficiency of compressor, η_{el} is electrical efficiency of compressor. These efficiencies are not significant differences in the value during the compressor operation should be considered as constants. Specific values of the above parameters for some types of compressors have been studied and published [22]. The volumetric efficiency, η_v, and the isentropic efficiency, η_s, are the parameters that significantly affect the compressor performance. In many studies, they are considered as a function of compression ratio [13] [17]. Actually, they depend on both evaporation and condensation pressures. To increase the reliability of the simulation model, the authors created the volumetric efficiency and the isentropic efficiency are functions of both evaporation and condensation pressure. The method of constructing the above functions has been presented by us in the previous study, the functions are determined by equations (4), (5) respectively [23].

$$\eta_v = a_v - \frac{b_v}{p_e} - c_v p_c \tag{4}$$

$$\eta_s = a_s - \frac{b_s}{p_e^2} - c_s p_c^2 \tag{5}$$

To identify the characteristic functions to describe the volumetric and isentropic efficiency of the compressor, three sets of experimental data corresponding to 3 working points were used. Solving the equations established from 3 experimental points will determine the coefficients a_v, b_v, c_v of the volumetric efficiency function and a_s, b_s, c_s of the isentropic efficiency function.

Evaporator

In the evaporator, the refrigerant receives heat energy from the air to changes the enthalpy and performs evaporation. The heat can be calculated through the variation of enthalpy or the heat transfer equation between refrigerant and air by equations (6), (7) respectively.

$$Q_e = m_r (h_1 - h_4) \tag{6}$$

$$Q_e = U_e A_e LMTD_e \tag{7}$$

In the HPWH simulation model, balancing the heat between formula (6) and (7) above will set the evaporation temperature, t_e.

Condenser

The heat transfer coefficient in the regions of the condenser is different. So, the condenser is divided into two zones, namely the de-superheating zone and the condenser zone. The amount of heat exchanged between the refrigerant and water can be determined by the following equations (8), (9) respectively.

$$Q_c = m_r \left(h_{2r} - h_3 \right) \tag{8}$$

$$Q_c = U_c A_c LMTD_c + U_{de-\sup} A_{de-\sup} LMTD_{de-\sup} \quad (9)$$

Expansion device

The process in the expansion device is an isenthalpic process. The enthalpy of the fluid before expansion valve is the same as the enthalpy of the fluid as it escapes through the valve using the following equation (10).

$$h_3 = h_4 \quad (10)$$

System simulation

The equations (1) - (10) presented above are the main equations that simulate HPWH's operation, detailing its constituent parts. Solving the equations will determine the operating parameters of the HPWH. To solve these equations, we selected the Engineering Equation Solver (EES) software to use because this is a general equation-solving program that can numerically solve thousands of coupled non-linear algebraic and differential equations. The program can also be used to solve differential and integral equations, do optimization, provide uncertainty analyses, perform linear and non-linear regression, convert units, check unit consistency, and generate publication-quality plots. A major feature of EES is the high accuracy thermodynamic and transport property database that is provided for hundreds of substances in a manner that allows it to be used with the equation solving capability [24].

The purpose of simulating the HPWH is to predict the performance of the unit under certain working conditions. First, the geometric parameters and input parameters were set. Second, the simulation equations are established in EES. Third, the EES software worked and calculated the operating parameters of the HPWH. An HPWH simulation software that has been developed for convenience is shown in Fig. 3. The software can calculate the key operating parameters of a heat pump, such as heat capacity, power capacity, and COP of HPWH under different operating conditions. The coefficients of performance (COP) of HPWH is defined with the typical definition by the equation (11).

$$COP = \frac{Q_c}{W_{el}} \quad (11)$$

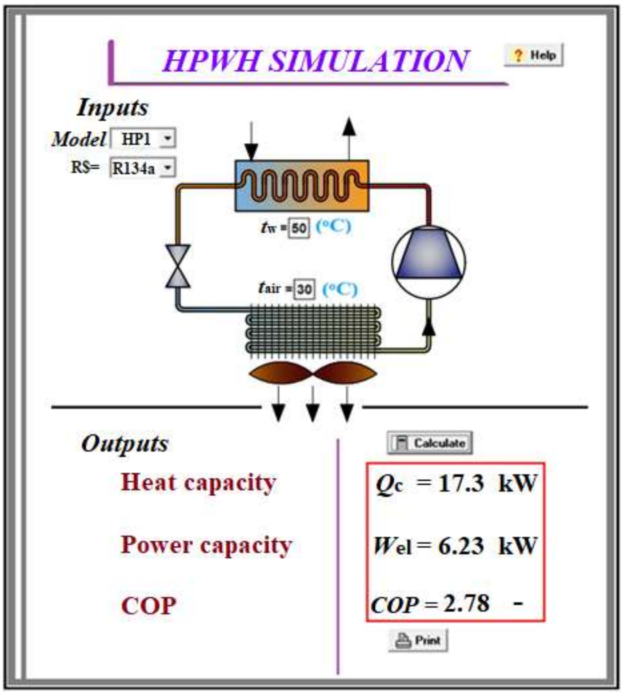

Figure 3. HPWH simulation software

EXPERIMENT VALIDATION

Fig. 4 shows the HPWH and its scheme that we used for the experiment. The HPWH was manufactured at Hanoi University of Science and Technology. Specifications of the key components of HPWH are shown in Table 1. The most interesting aspect of the HPWH is that we designed and manufactured a Shell-Tube condenser for easy assembly and convenience to clean the internal heat exchangers. The HPWH is directly connected to a water tank. The temperature sensors have been installed on the heat pump, as shown in Fig. 4 to measure the air temperatures and the temperatures of water through the heat pump. The measured values will be used as input parameters for heat pump simulation to verify the heat pump simulation model. In this study, the simulation model is verified by comparing COP to be predicted and measured. The comparison results and some discussions are presented in the following section.

Table 1. Actual HPWH specification

Components	***Specification***
Compressor	Bitzer, model 4CC-9.2Y Refrigerant: R134a
Condenser	Shell-Tube, “multi body” type Dimension (L×W×H): 966×100×800 mm
Evaporator	Finned evaporator Dimension (L×W×H): 1160×220×960 mm
Expansion valve	TXV, model TEN5-3.7

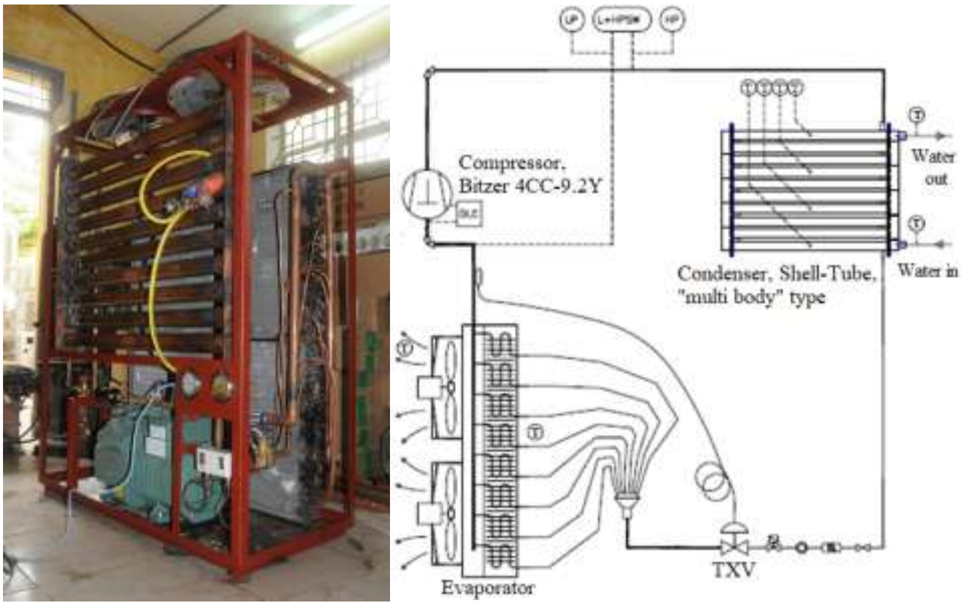

Figure 4. Picture of the actual HPWH and its schematic diagram

RESULTS AND DISCUSSION

Fig. 5 shows the effect of the inlet water temperature on the COP of the HPWH. In the experiments, the period for collecting experimental data was 5 minutes. The inlet water temperature increased from 44 to 56 °C, but it was uneven because of the water from the heat pump circulated through an active water tank. The air temperature around the HPWH is 28.6 ±0.5 °C. Therefore, the air temperature used in the simulation was 28.6 °C. From these results, as shown in Fig 5, we found that the COP decreases from with increase in the inlet water temperature. In comparing predicted COP and measured COP values, the maximum difference between the predicted and measured COP is 0.19, which corresponds to 5.0%. The result indicates that the predicted values are in good agreement with the measured values.

The COP of HPWH depends on many factors, such as the characteristics of components of HPWH, the refrigerant mass flow rate, the working conditions used, etc. Among the above, the air temperature and the inlet water temperature are two key working conditions parameter. Fig. 6 provides an overview of the dependence of COP on water inlet temperature of HPWH and air temperature into the evaporator. COP of HPWH under typical working conditions in Vietnam has been investigated. The range of the air temperature was from 10 to 35 ^{o}C, and the range of the inlet water temperature was from 30 to 55 ^{o}C. The results show that when the air temperature through evaporator increases and the temperature of hot water through condenser decreases the COP of the HPWH increases. The smaller the temperature difference between air and water, the higher the COP of the heat pump. From the figure, it can be seen that the maximum and minimum COP were 5.5 and 2.2, respectively. When the hot water temperature is 50 °C, the COP value varies from 2.5 to 3.8, depending on the air temperature. These results are consistent with many published results of other research groups [15][25][26]. When the air temperature is low (10 ^{o}C), the COP of the heat pump is poor (from 2 to 3), in this case, to increase COP, the hot water temperature should be reduced.

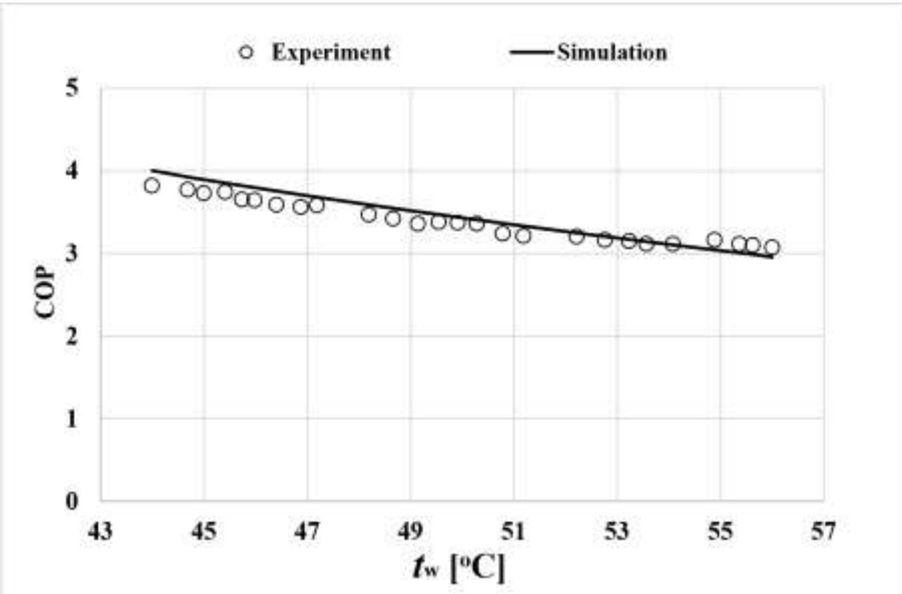

Figure 5. Comparison of the predicted and measured COP when the inlet water temperature changes

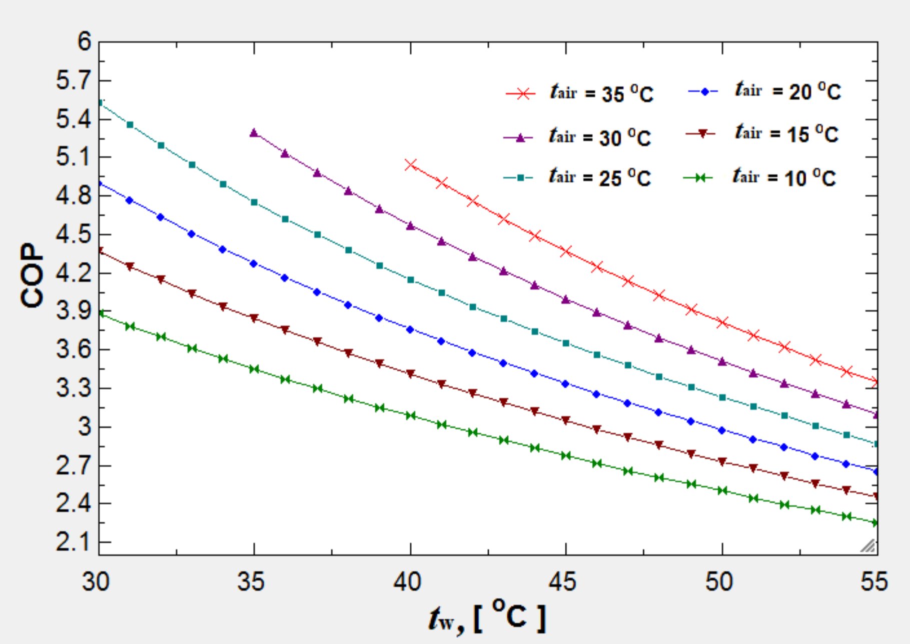

Figure 6. COP dependence on water inlet temperature and air temperature

CONCLUSIONS

In this study, a simulation model for HPWH was developed based on the component models. The volumetric efficiency and isentropic efficiency of the compressor are determined by three sets of experimental data corresponding to three sets of operating conditions. Additionally, this simulation model has been validated by experimenting with an actual HPWH. The effects of the air temperature and the inlet water temperature on the COP of HPWH were investigated. The comparison between simulation and experimental data showed that the maximum difference between the predicted and measured COP was 5.0%. Simulation results are in good agreement with the experimental data, which lead to conclusion that the HPWH simulation model is high precision. The HPWH simulation model is used to study the COP of HPWH under different operating conditions. Under typical operating conditions in Vietnam, the range of the inlet water temperature was from 30 to 55 °C, and the range of the outside air temperature was from 10 to 35 °C; the COP of HPWH ranges from 2.2 to 5, confirming the high energy efficiency when using HPWH.

NOMENCLATURE

A	area	m^2
a, b, c	coefficient of efficiency function	-
COP	coefficient of performance	-
h	enthalpy	kJ/kg
v	kinematic viscosity	m^2/s
η	efficiency	-
m	mass flow rate	kg/s
n	rotary speed	rps
T	temperature	K

p	pressure	bar
Q	heat	W
U	heat transfer coefficient	W/(m^2·K)
W	power	W
LMTD	log mean temperature difference	K

SUBSCRIPTS

c	condenser
e	evaporator
de-sup	de-superheating
w	water
r	refrigerant
me	mechanical
el	electrical
v	volumetric
s	isentropic, swept

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