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Quantification of model uncertainty of water source heat pump and impacts on energy performance

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Abstract. Water source heat pump (WSHP) systems are widely used for cooling and heating due to high efficiency. Accurate modeling of water source heat pump systems is the basis for performance prediction, design and control optimization. However, various uncertainties exist in the simulation and affect the simulation results, which can be categorized into parameter uncertainties and model form uncertainties. Without considering these uncertainties, the performance of water source heat pump systems would be overestimated or underestimated and then affect the decision of stakeholders. The models of heat pumps are especially important for accurate simulation. This paper therefore attempts to quantify the uncertainty of heat pump models and associated impacts on the energy performance of water source heat pump systems. Based on the experiment data of a heat pump, 13 models of heat pumps are examined. The energy performance of the system considering uncertainties in the heat pump model can also be obtained. Results show that the uncertainty in heat pump models can result in a deviation of around 30.55% in the energy consumption. The energy saving potential of WSHP systems can vary between 28.04% to 48.22%. It demonstrates that the uncertainties in models affect the system performance significantly. It is therefore highly recommended to take the uncertainty of heat pump models into account in building energy prediction and design optimization.
Keywords: Uncertainty quantification; WSHP system; energy saving; model uncertainty

1. Introduction

The WSHP system plays an important role in heating and cooling of buildings due to high energy efficiency and low emissions [1]. The research of WSHP systems can based on experiments and simulation. Experiment studies are very valuable but usually need high expenditure of time and costs. For some studies, it is impossible to conduct experiments such as design optimization or performance prediction in the life cycle, and then simulation of WSHP systems is necessary.

Many studies regarding to the performance assessment, design optimization and control optimization are based on simulation. Wang et al. [2] adopted a numerical simulation method to optimize the water-intake design option aiming to improve the energy efficiency for an open-loop surface WSHP system. An energy prediction method is proposed by [3] based on data partitioning techniques and operation patterns of pumps. It concludes that the method can improve the performance of prediction.

Heat pump is the key component of the WSHP system and modelling of heat pumps plays a significant role in the simulation of WSHP systems. Various heat pump models can be found in existing studies and they can be generally grouped into two categories. One is the theoretical model, which is mainly used for dynamic simulation such as control optimization [4]. The other is the empirical model, which is usually obtained based on experiment data without simulating the details of heat pumps. These models are mainly used for energy performance assessment and design optimization [5]. Even for the empirical models, considerable uncertainty exists and will affect the simulation results, which can be taken as the model uncertainty of heat pumps. When the uncertainty is not addressed properly, the system performance evaluation will deviate from the true values, resulting in unreasonable or even incorrect decisions.

Uncertainties in building energy simulation have attracted increasing attentions. To avoid inappropriate system design, A framework was proposed for HVAC system sizing based on uncertainty analysis and sensitivity analysis to replace the traditional method using design day and safety factor [6]. The impacts of uncertainty in other parameters such as user behavior and physical parameters on thermal performance and energy consumption of buildings were analyzed [7]. The above review shows that the uncertainties in buildings energy systems are widely investigated. However, the uncertainties in the model of heat pumps and the impacts of uncertainties on the energy performance of WSHP systems are not addressed yet.

This paper attempts to investigate the uncertainty of heat pump models and quantify the impacts on energy performance of WSHP systems. 13 models of water source heat pump are selected and built using manufacture data. By integrating these models in a WSHP system for an office building, the uncertainty of heat pump model and impacts can be quantified.

2. The model uncertainty quantification method and steps

The method to quantify the uncertainty of the WSHP model is shown in Figure 1 and detailed steps are introduced as follow.

1. Load calculation. By importing the variables such as weather data, building design and indoor conditions into the building simulation tools, the annual loads can be obtained. Weather data of the TMY (typical meteorological year) are used in this paper. Indoor conditions are determined according to design guidelines or manuals.

2. WSHP system design. Based on the cooling and heating load, the WSHP system can be designed. To quantify the impacts of heat pump model uncertainty on the energy performance of WSHP system, a conventional system using chillers for cooling and boilers for heating is also designed. The capacity of WSHP system is determined based on the peak cooling demand of the building. The number of heat pumps, chillers, boilers, cooling/chilled water pumps and cooling towers is also determined in this step.

3. System simulation. The WSHP system is simulated via TRNSYS 18. The source of the WSHP system in this study is lake water. Whose temperature is evaluated using Eq. 1[1]. where t_w is inlet lake water temperature, ℃, t_a is air dry bulb temperature, ℃. For the model of air handing unit (AHU) in cooling/ heating mode, Type 508c/Type 753e is used. Type 742 is used to model the pumps. The secondary pump is variable speed to maintain the supply and return temperature differential.

$$t_w=0.74t_a+4.22 \tag{1}$$

4. Uncertainty quantification of heat pump models. The uncertainty of heat pump models is quantified by selecting a number of models commonly used in existing studies. Based on collected data from manufacture or experiments, each model can be built and validated. Detailed description of these models is provided in Section 3.

5. Results analysis. Importing each heat pump model in the WSHP system, the annual performance can be obtained. The energy saving potentials of WSHP systems compared with the reference system considering model uncertainties of heat pumps are analyzed.

3. Heat pump model selection and validation

Totally 13 heat pump models are selected could be classified into two types: the model considering the impacts of partial loads and the model only concerning the full load, as summarized in Table 1. It shows that all full load models are expressed as polynomial functions of water temperature at user side or source side. For M1~7, data under full load conditions only are needed. The impacts of partial load conditions on the performance of heat pumps are considered in M8 ~12 but the expressions are quite different. M13 is the water-to-water heat pump component of TRNSYS: Type927. By inputting the user side return water temperature and the source side return water temperature, the correction factor for heat pump capacity and power consumption can be obtained from the external data file provided based on the manufacture data. In some models, the performance of heat pumps also relates to the flowrate of water flowrate at both user and source side. In this study, the cooling water and chilled water flowrates entering the heat pumps are assumed to be constant.

Table 1. Modeling of 13 selected heat pumps

Model number & source	Model formula	Consider PLR or not
M1 [8]	$W=a+b\cdot T_{ui}+c\cdot T_{ui}^2+d\cdot T_{si}+e\cdot T_{si}^2$	NO
M2 [9]	$COP=a\cdot t_{si}+b\cdot t_{sinkmean}+c\cdot t_{si}^2+d\cdot t_{sinkmean}^2+e\cdot t_{si}\cdot t_{sinkmean}+f$	NO
M3 [10]	$\frac{W}{W_{ref}}=a+b\cdot\frac{t_{uo}}{t_{uo,ref}}+c\cdot\frac{t_{si}}{t_{si,ref}}$	NO
M4 [11]	$COP=a\cdot t_{si}+b$	NO
M5 [12]	$W=a\cdot t_{si}+b$	NO
M6 [12]	$COP=a\cdot t_{si}^3+b\cdot t_{si}^2+c\cdot t_{si}+d$	NO
M7 [5]	$COP=a+b\cdot t_{so}+c\cdot t_{uo}+d\cdot t_{so}\cdot t_{uo}$	NO
M8	$COP=COP_{basic}\cdot\psi_{cond,tem}\cdot\psi_{evap,tem}$ $COP_{basic}=a\cdot exp\left(\frac{b}{PLR+c}\right)$ *cooling mode:* $\psi_{cond,tem}=a\cdot t_{si}^2+b\cdot t_{si}+c$ $\psi_{evap,tem}=a\cdot t_{uo}^2+b\cdot t_{uo}+c$ *heating mode:* $\psi_{cond,tem}=a\cdot t_{uo}^2+b\cdot t_{uo}+c$ $\psi_{evap,tem}=a\cdot t_{so}^2+b\cdot t_{so}+c$	YES
M9 [13]	$W=W_{ref}\cdot CAPFT\cdot EIRFT\cdot EIRFPLR$ $CAPFT=\frac{CAP_C}{CAP_{ref}}=a+b\cdot\frac{t_{uo}}{t_{uo,ref}}+c\cdot\frac{t_{si}}{t_{si,ref}}$ $EIRFT=\frac{\frac{W_C}{CAP_C}}{\frac{W_{ref}}{CAP_{ref}}}=a+b\cdot\frac{t_{uo}}{t_{uo,ref}}+c\cdot\frac{t_{si}}{t_{si,ref}}+d\cdot\left(\frac{t_{uo}}{t_{uo,ref}}\right)^2$ $+e\cdot\left(\frac{t_{si}}{t_{si,ref}}\right)^2$ $EIRFPLR=\frac{W_C}{W_{ref}}=a\cdot PLR^2+b\cdot PLR+c$	YES
M10 [14]	$COP=PLE\cdot COP_{full\ load}$ $PLE=a\cdot PLR^3+b\cdot PLR^2+c$ $COP_{full\ load}=a+b\cdot t_{evapsat}+c\cdot t_{condsat}+d\cdot t_{evapsat}^2+e\cdot t_{evapsat}\cdot t_{condsat}$ $+f\cdot t_{condsat}^2+g\cdot t_{evapsat}^3+h\cdot t_{evapsat}^2\cdot t_{condsat}+i\cdot t_{evapsat}\cdot t_{condsat}^2+j\cdot t_{condsat}^3$	YES
M11 [5]	$COP=a+b\cdot PLR+c\cdot(t_{uo}-t_{si})+d\cdot PLR\cdot(t_{uo}-t_{si})$	YES
M12 [15]	*cooling mode:* $W=a+b\cdot(t_{si}-t_{uo})+c\cdot(t_{si}-t_{uo})^2+d\cdot Q_c+e\cdot Q_c^2+f\cdot(t_{si}-t_{uo})\cdot Q_c$	

heating mode: $W=a+b\cdot(t_{uo}-t_{ev,m})+c\cdot(t_{uo}-t_{ev,m})^2+d\cdot Q_h+e\cdot Q_h^2+f\cdot(t_{uo}-t_{ev,m})\cdot Q_h$	YES

Note: W is the power of the heat pump, CAP is the nominal capacity, Q is the cooling/heating supplied by heat pump, t is the water temperature, $t_{sinkmean}$ is the average temperature on the user side of heat pump, a~f are the coefficients, ψ is the correction factor, the subscripts cond, evap, tem, ref, C, c, h, u, s, i and o represent the condenser, the evaporator , temperature, the reference condition, the real condition, the cooling mode, the heating mode, the user side, the source side, inlet and outlet respectively.

Performance data of a heat pump with a cooling/heating capacity of 1049 kW/1169kW are obtained from a manufacturer, including the power consumption and COP under different supply temperatures to users, return temperature from the source water and part load ratios (PLRs), as shown in Fig.2. Parameters in all the above models were obtained by fitting the data. The modelling results are shown in Table 2. It shows that the R2 (regression value) for all the models is higher than 0.9 under both heating and cooling mode. For M13 which is Type 927 in TRNSYS18, it is realized by supplying data in the external files so no regression result is provided.

Table 2. Regression values of 13 heat pump model by fitting the manufacture data

Model number		M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
R^2	*cooling*	0.9631	0.989	0.9732	0.9981	0.9984	1	0.9876	0.9932	0.9847	0.9902	0.9622	0.9907
	heating	0.9991	0.9989	0.9994	1	0.998	1	0.9975	0.9932	0.9981	0.9993	0.9108	0.9996

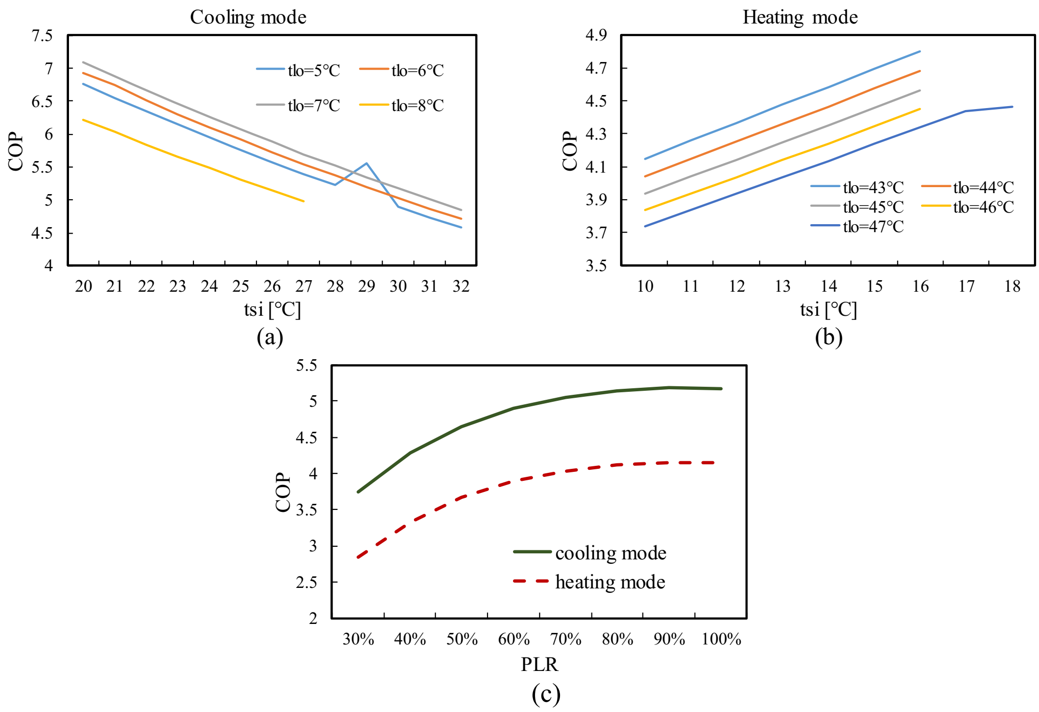

Figure 2. COP of the heat pump under different temperature and PLR from the manufacturer data

4. System description of the WSHP for an office building

An office building in Wuhan is taken to investigate the model uncertainty of heat pump and the impacts on energy performance as shown in Figure 3. The gross floor area of the building is approximately

32,000 m^2. The envelope structure is mainly glass curtain wall. EnergyPlus was used to calculate the annual hourly cooling and heating load of the building as shown in Figure 4.

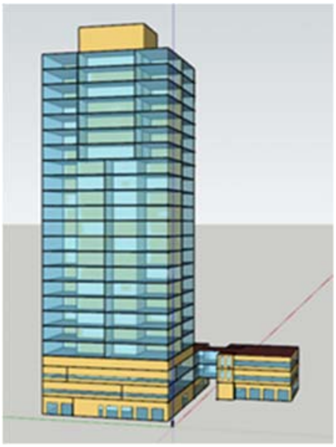

Figure 3. The building model for Energyplus

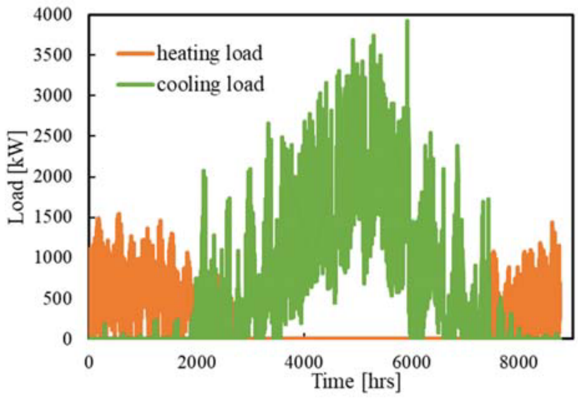

Figure 4. Annual hourly loads of the building

WSHP system is selected to supply cooling and heating for the building as shown in Figure 5. Four heat pumps with a capacity of 1049 kW in cooling mode and 1169 kW in heating mode are selected. The head of the cooling water pump, primary chilled water pumps and secondary chilled water pump is assumed to be 20m, 15m and 25m respectively. The reference system using chillers for cooling and boilers for heating was also simulated to show the impacts of model uncertainty on the energy performance. The model of the boiler is Type122 in TRNSYS with a rated capacity of 1745kW and efficiency of 0.94.

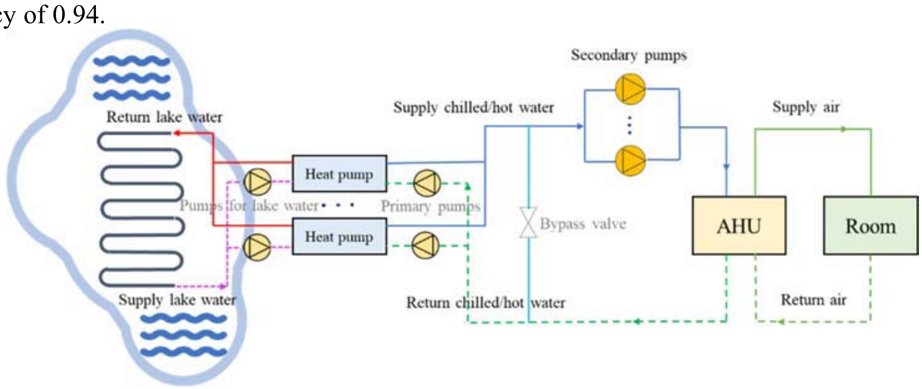

Figure 5. The schematic diagram of the WSHP system

5. Performance of the WSHP system considering model uncertainty of heat pump

The annual energy consumption of WSHP system using different models of heat pump and the reference system can be obtained. The annual energy consumption and the energy saving compared with the reference system (3.034×106 kWh) is shown in Figure 6. It shows that the energy consumption deviation of the WSHP system using different models is quite significant, varying between 1.57×106 and 2.18×106 kWh. By taking M9 as the base model, which is more detailed, the energy consumption of the WSHP can vary between -6.05% and 30.55%. which is very large. The energy saving of WSHP system compared with the reference system is also shown in Figure 6 and ranges from 28.04% to 48.22%. It can be seen the difference is very large, which can be up to 20% using different models of heat pumps. When the models of heat pump considering the impacts of partial load are used, the difference in energy saving is much smaller, which is between 0.26% to 5.51%. It shows that the uncertainty of heat pump model can affect the annual energy performance of WSHP system significantly.

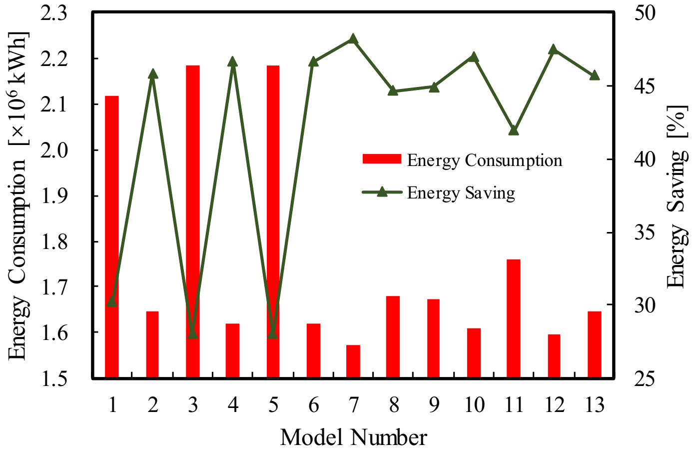

Figure 6. Annual energy consumption and energy saving of the WSHP system

The monthly energy consumption of WSHP system using different models of heat pump is shown in Figure 7 (a). It shows that the monthly energy consumption of WSHP system under different models varies between -11.92% and 55.55% by taking M9 as the base case. In Figure 7 (b), the monthly energy saving rate ranges from -39.53% to 71.65%. There is negative energy saving for M 1, M 3, and M 5 from April to October, which is consistent to the results in Figure 6. The largest and smallest difference of monthly energy saving using different models is in January and October respectively, with 9.4% (January) and 56.36% (October).

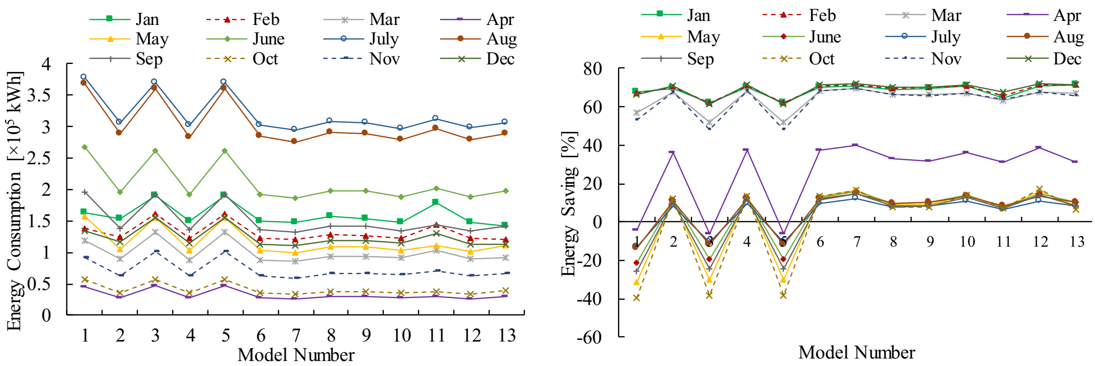

Figure 7. Monthly energy performance of WSHP systems using different models of heat pump

The energy performance of the WSHP system on the typical summer day (July 24th) and winter day (January 8th) is shown in Figure 8. It shows that the energy consumption of the WSHP system using different models varying between 14284 and 17418 kWh on the summer day. The deviation is -2.99% and 18.49% taking the M9 as the base model. The energy saving varies between -10.75% and 9.18%. For the typical winter day, the energy consumption varies between 8849 and 12314 kWh on the winter day, which is -10.78% and 24.16% of deviation. The energy saving varies between 60.6% and 71.69%. It can be seen that the energy saving difference on the cooling day is larger than that on the heating day, which indicates that the model uncertainty has larger effects on the cooling mode.

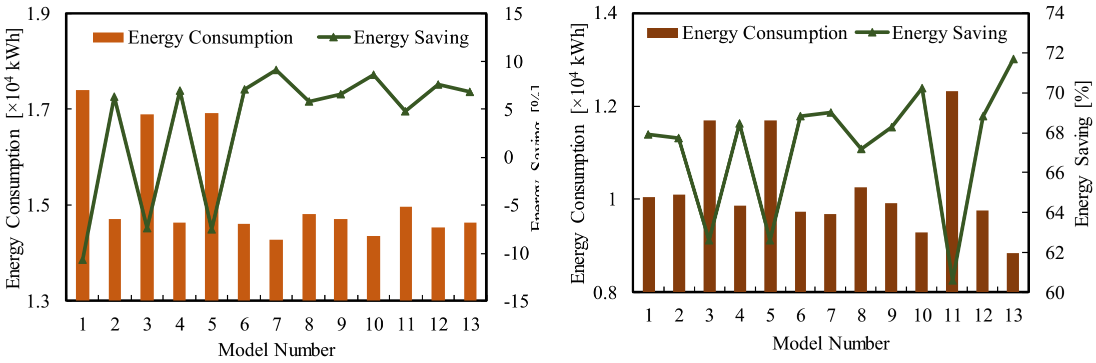

Figure 8. Energy performance of the WSHP system on a typical summer day and winter day

6. Conclusion

This paper attempts to quantify the uncertainty of heat pump model and impacts on energy performance of WSHP systems. By testing and comparing 13 heat pump models, the performance of WSHP systems can be obtained. According to the results and analysis, the following conclusions can be obtained:

The influence of heat pump model uncertainty on the performance of WSHP system cannot be ignored. The annual energy consumption of WSHP system can vary up to 30.55%. The energy saving compared with the chiller & boiler system ranges from 28.04% to 48.22% and the difference can be up to 20%.

The monthly energy consumption of WSHP system under different models varies between -11.92% and 55.55% by takingM9 as the base case. The energy saving varies between -39.53% and 71.65%. For different months, the difference in energy saving resulting from the heat pump model uncertainty is between 9.4% and 56.36%.

The model uncertainty of heat pump has a larger impact on the cooling performance of the WSHP system. For the cooling day, the energy consumption of WSHP system under different models varies between -2.99% and 18.49% by taking M9 as the base case. The energy saving varies between -10.75% and 9.18%. Energy performance of WSHP system is similar when using models that consider the impacts of PLR compared with those only involves the full load condition. It is therefore recommended to adopt the heat pumps models that consider the effects of partial loads.

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