

VARIABLE CAPACITY HEAT PUMP SYSTEMS, MODELING AND SIMULATION

*H. Madani, MSc, P. Lundqvist, Professor, J. Claesson, PhD,
Div. Applied Thermodynamics and Refrigeration, Dept. Energy Technology,
Royal Institute of Technology, KTH, Stockholm, Sweden*

Abstract: Variable speed compressor is one of the most promising ways to modulate the capacity of heat pump units. The paper describes some common obstacles in the evaluation of variable speed heat pump systems. The inconsistencies between the compared system components, the complexity in the measurement of some detailed parameters, too much focus on unit efficiency solely, but also not considering the effect of system dynamics are some of the mentioned problems. Dynamic modelling and simulation of a heat pump system taking all system components into consideration and validation of the model based on experiments are suggested as the solution. This paper describes a parameter estimation approach to variable speed heat pump unit modelling that requires a relatively low demand of measured input data. The outputs of the model are a number of parameters such as total isentropic efficiency of compressor as a function of frequency, superheat temperature and sub-cooling temperature, etc. Making use of the model provides the opportunity to evaluate the dynamics of the whole system including building and heat source in TRNSYS.

Key Words: *heat pump, capacity control, modeling, simulation, variable speed*

1 INTRODUCTION

The efficiency of typical heat pump units in residential application can be significantly improved by employing appropriate control strategies in heat pump systems including the heat pump unit, the heat sink (the building), and the heat source such as ground, outside or exhaust air, etc. A large share of these losses comes from the discrepancy between the unit output heating capacity and the required heat demand. For instance, in a hydronic heating distribution system such as radiator or floor heating, an over-capacity of the heat pump unit results in an unnecessary large temperature increase from the return water temperature to the heat pump outlet temperature. For outside temperature higher than the balance temperature¹, the heat pump outlet temperature will be higher than the necessary supply temperature, so the difference between the required supply temperature and the heat pump outlet temperature reduces the Seasonal Performance Factor of the system (SPF).

The conventional on/off control of heat pump unit is the most common way to overcome temperature mismatch losses. In on/off controlled heat pump units the compressors are switched on or off by aid of a control algorithm estimating the discrepancy between building heat demand and heat pump capacity. Several authors have showed how the mean temperature during the on time periods is higher than the needed mean temperature in an on/off controlled unit. For example, (Fahlen 2004) and (Karlsson 2007) suggests that this may lead to a 2% COP reduction/K.

¹ The outdoor temperature where building heating demand matches heat pump capacity

Furthermore, frequent switching of a compressor on and off introduces so called "cycling losses". The reason for these losses are the migration of the refrigerant after cut-off and the need to heat up the thermal mass of the system - mainly the heat exchangers and the compressor at the start up after a long off period. For example, according to Henderson (2000), in air/air heat pumps, the losses due to the thermal inertia of the compressor and the refrigerant migration during the off-period accounted for 4-11% reduction in efficiency.

Moreover, if the system is designed to cover 100% of the annual load and consequently eliminate the supplementary heat in the system, an intermittent controlled heat pump unit will always be oversized and it will have too many on/off cycles increasing the importance of cycling losses. A lower mean evaporation temperature than the required one in an on/off controlled heat pump unit also increases the need for defrosting in air source heat pumps.

Due to the mentioned obstacles and losses caused by on/off controlled heat pump units, finding better alternative control has been considered as a significant step by many heat pump manufacturers. Variable speed compressor has been proposed by many authors as one of the most promising ways in capacity control of heat pump and refrigeration systems having a great potential for energy saving (Zubair 1989); (Sheldrake 1991); (Qureshi 1996); (Claesson 2002). However, there have been some limitations and difficulties hindering the researchers to draw a clear practical conclusion and pragmatic results, from either experiment or modelling of variable capacity systems. It is also very difficult to compare and generalize the results from different studies.

Some of the reasons are:

1. Inconsistency between the compared systems components (different type of compressors or heat exchangers),
2. Focus solely on the heat pump unit efficiency and neglecting the behaviour of other parts of the system,
3. Lack of knowledge about the losses induced by variable speed compressor due to complex measurement process required,
4. Neglecting the dynamics of the whole system, including heat source and heat sink (residential building in our case).

The inconsistency between the compared systems components is typical in experimental comparative analyses. For instance, the seasonal performance factor of a variable speed heat pump system is compared to one of a single speed on/off controlled unit whereas the heat load and heat sink conditions are completely different or, even more commonly, the compressor or refrigerant types are different in these two cases. Obviously, some limitations and obstacles hinder the researchers to examine different control methods on heat pumps with exactly the same specifications such as the same compressor, refrigerant, or building. So, the most appropriate way seems to be modelling the system and applying available experimental data to validate the model. It is then feasible to compare the performance of the different control strategies on the same systems.

Another common phenomenon is a strong focus on the super-efficient heat pump unit forgetting the undeniable role that the other parts of the system such as building dynamics, temperature level of the heat distribution system, or heat source characteristics can play to increase the system COP. A complicated and costly improvement of the heat pump unit may easily be offset by a small change in the load side conditions. This issue demonstrates the necessity to look at the heat pump system in a wider sense covering the building, building inhabitants, heat source and control units all as the parts of the system.

A common conclusion in some of the investigations are that heat pump systems with variable speed compressor in theory has a great potential to improve heat pump unit COP or SPF; however, because of other losses imposed by the variable speed compressor, the actual

outputs are however not as good as expected. The new losses introduced can stem from the frequency inverter or changes in volumetric or total efficiencies of compressors due to frequency changes. Obtaining sufficient knowledge about what exactly happens to the compressor efficiencies when the frequency is varied or where the new inefficiencies come from is required in order to understand the advantages of variable speed and minimize the disadvantages.

Another often neglected significant characteristic of the system usually is the dynamic behaviour of the system; boundary conditions are time dependant and different sub-systems have different time constants. Certain parameters such as outdoor or indoor temperature of buildings change relatively slowly; whereas, other such as solar insolation and tap water use are more rapid. Going into all these details of heat pump unit control needs a very short time step (a few seconds) through the investigation; whereas, the control issues in the whole system in a wider sense can be hourly-based. Heat source and heat load are being dynamically altered by boundary conditions such as user behaviour or climatic changes. Thermal inertia of the heating system is another significant issue which was only considered by a few investigations before (Sakellari et al., 2006). Consequently, carrying out a research considering all these dynamic aspects of the system is a challenge.

2 MODELING AND SIMULATION PROCEDURE

2.1 The aim of the model

In order to fulfil the mentioned requirements, the development of a comprehensive dynamic model of a variable capacity controlled heat pump system is necessary. This model must not only include a detailed model of a heat pump unit, but also handle crucial factors such as building thermal inertia, type of heat distribution system, heat source and heat load dynamic behaviour and so on. Dynamic simulation of such a model provides this opportunity to:

- compare exactly the same systems with different control methods and strategies
- analyze the system performance in a wide range of conditions
- facilitate a greater understanding of the losses in a heat pump unit when applying different control strategies (e.g., the compressor volumetric and total efficiencies change when the frequency is changed).

2.2 The type of the model

One of the vital questions to handle before the modeling quest is what our expectations are from the model and how the model should look to fulfill our requirements. In our case, the heat pump model should

- be able to simulate the system behavior in a transient condition,
- require a small amount of measured data since good data are not easily accessed,
- provide a convenient interaction between the system's components,
- yield realistic results in a wide range of conditions, etc.

There is a large variety in possible models of heat pumps and refrigeration units. The models can be very simple black-box model receiving the source side temperature from the heat source and load side temperature from the building yielding some general outputs such as heating capacity and compressor work based on the performance matrix (from tests) of the heat pump in question. Another extreme is the very detailed thermodynamic model, often referred to as a deterministic model, which use a large amount of test data for each component which are not so simple to obtain. These models yield a large amount of detailed outputs about the components as well. There are a lot of other models falling between these

two extremes. The parameter estimation model is one of them. It uses test data which is not too hard to achieve; the model/program then estimates some characteristic parameters for the components. It is not expected that the estimated parameter values match the precise specification of the heat pump components; however, it uses a minimum of internally measured data to show the losses behaviour of the components. The model is also easy to validate with a relatively small number of measurements.

2.3 The simulation tools

EES (Engineering Equation Solver)² is used as the simulation tool for the heat pump unit model. Besides, having a comprehensive database of refrigerants' properties, it is also able to carry out dynamic modelling in the presence of all other parts of the systems such as building and heat source model, thanks to the co-solving capability of EES and TRNSYS³.

2.4 Model modification

The parameter estimation model type has previously been used in heat pump modelling by several authors such as Bourdouxhe et al. (1994); Jin et al (2002). However, there are some assumptions in their models which may not be applicable in a heat pump system with a variable speed compressor. So, the first step in this study is to investigate whether these assumptions are appropriate for variable speed heat pump units or not.

2.4.1 The assumption of a constant UA value for condensers and evaporators

At this stage, an investigation is done to find if an estimation of a constant UA value for condenser and evaporator through the parameter estimation model is reliable enough for variable capacity heat pumps. In order to achieve this aim, a parameter estimation model is made in order to estimate constant UA values for condensers and evaporators based on:

- Approach heat sink temperature to condenser (water side) called load side temperature
- Approach heat source temperature to evaporator (brine side) called source side temperature
- The heating power from condenser
- The cooling power from the evaporator
- The water side (load side) mass flow rate
- The brine (source side) mass flow rate

Accordingly, the results from the model developed in this work are compared to the measured condensation and evaporation temperatures (see figure 1 and 2). In spite of a relatively wide range of compressor work and heating capacity (see table 1), these figures show that it seems feasible to avoid the measurement of condensation and evaporation temperatures at each point; estimation of constant UA values in the parameter estimation model seems to yield reasonable results.

² <http://www.fchart.com/ees/ees.shtml>

³ <http://sel.me.wisc.edu/trnsys/>

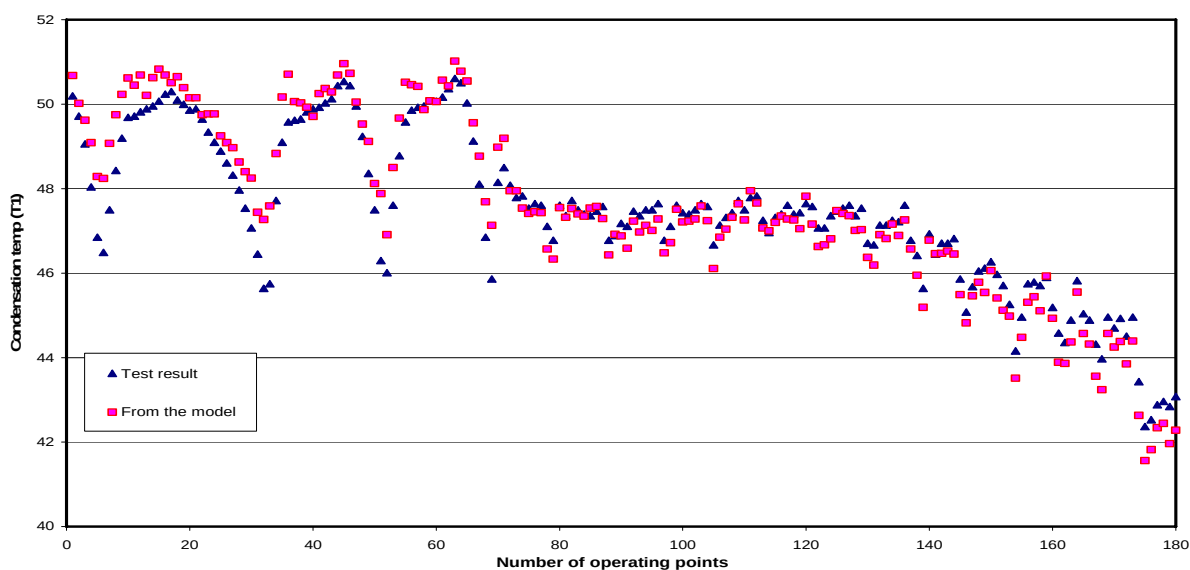


Figure 1: Condensation temperature, test vs. calculated from the model

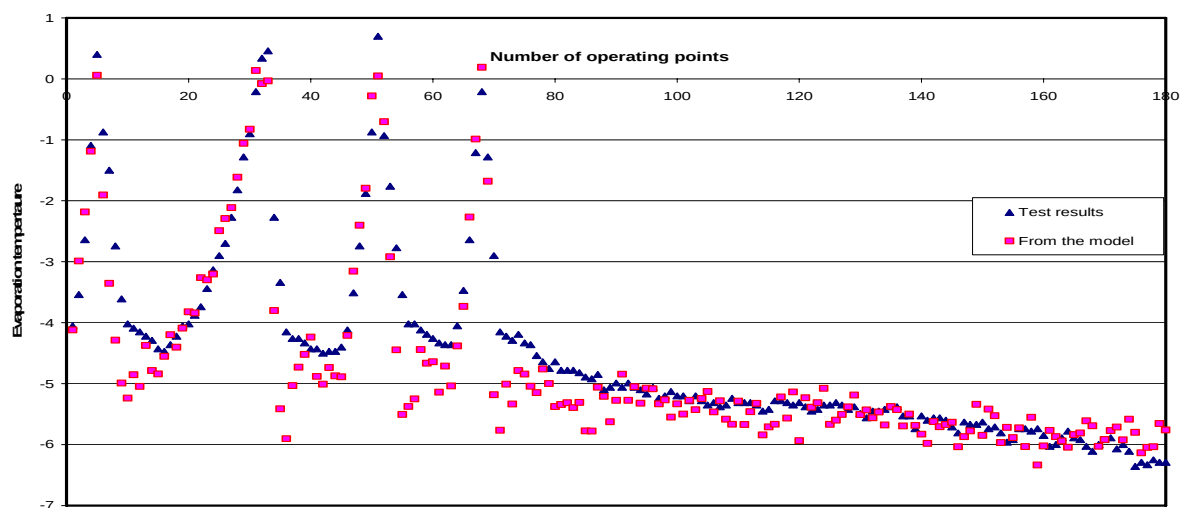


Figure 2: Evaporation temperature, test vs. calculated from the model

Table 1; Range of parameters in the investigated operating points

Parameter	Maximum value	Minimum value	Average value
Compressor work (kW)	2,98	1,36	2,52
Condenser heat transfer rate (kW)	10,63	5,24	9,05
Approach heat sink temperature to the condenser (°C)	43,19	32,99	40,35
Approach heat source temperature to the evaporator (°C)	7,81	5,93	6,79

2.4.2 Assumption of constant superheat temperature

Jin et al. (2002) further assumed constant superheat temperature in their heat pump model which here is estimated through the model. As shown in figure 3, experiments show a considerable fluctuation in the superheat temperature for the variable capacity heat pump unit. Furthermore, the constant value obtained from our model can not represent this fluctuation (it is very close to the upper limit). So, it seems inappropriate for the model to estimate a constant superheat temperature.

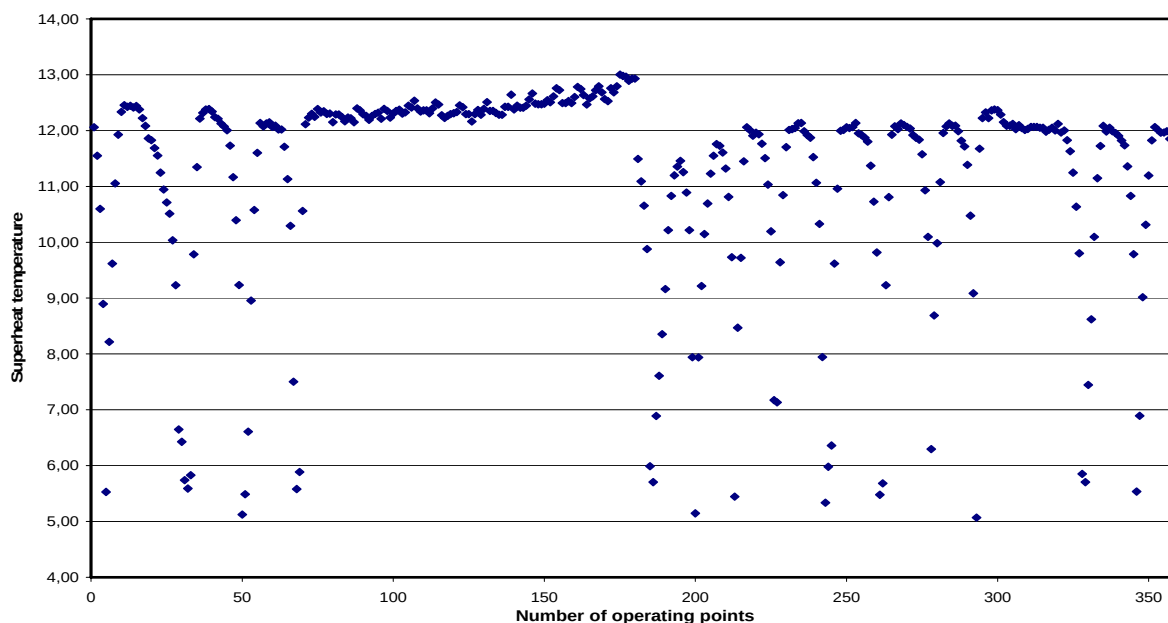


Figure 3: Superheat temperature changes- experiment result

In the heat pump system with variable speed compressor when working at part load, the lower heat transfer-rate leads to lower temperature differences in the heat exchangers and thus higher evaporating (suction) pressure. If the pressure difference across the expansion valve's membrane is set to be constant (by adjusting the spring), the higher evaporation pressure leads to lower superheat temperature. Figure 4 shows how the superheat temperature decreases by an increase in evaporation pressure. This figure depicts two different behaviours of superheat temperature: one in evaporation pressures less than 280 kPa and one for evaporation pressures more than 280 kPa. These different behaviours can be attributed to too small expansion valve or low charge of refrigerant; in low evaporation pressures (high loads), the expansion valve is fully open but due to its small size, it can not provide sufficient refrigerant for evaporation which leads to too high superheat temperature.

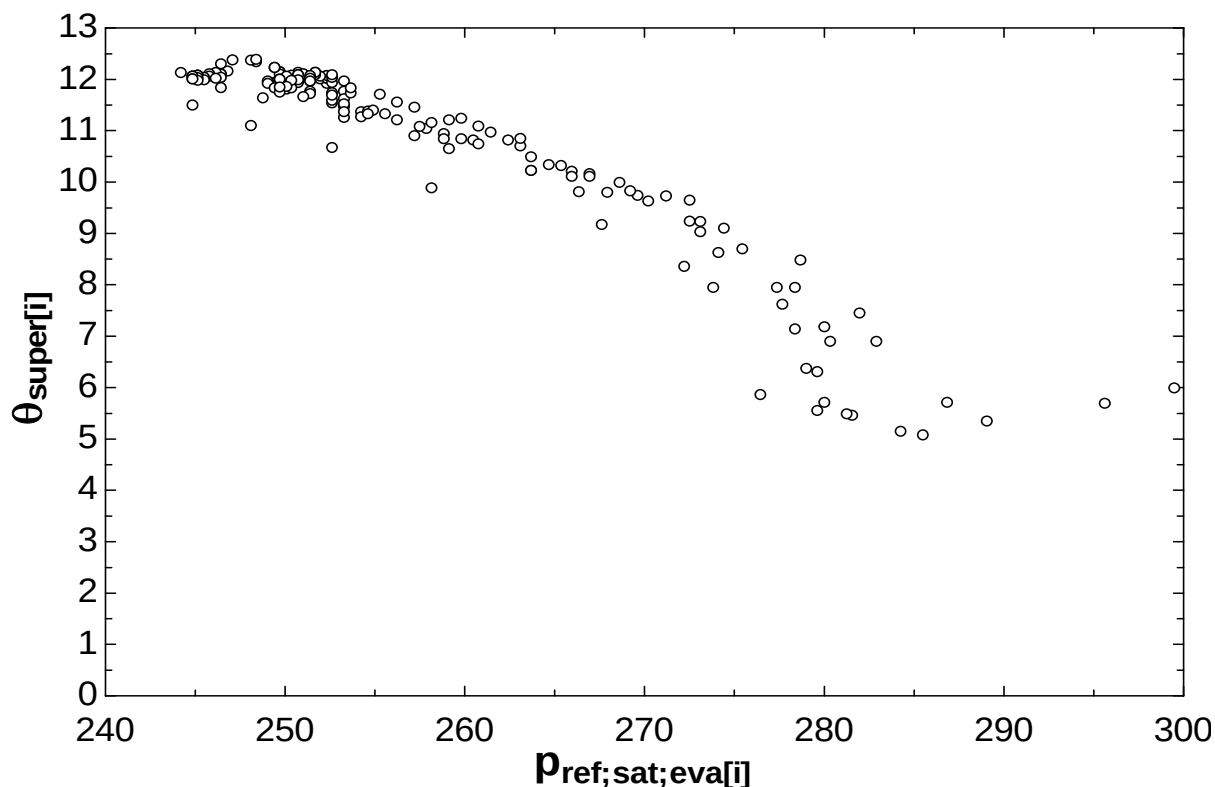


Figure 4: superheat temperature versus saturated evaporation pressure of refrigerant (kPa)-experiment result

2.4.3 Assumption of constant sub-cooling temperature

Figure 5 shows how the sub-cooling temperature increases slightly by increasing the condensation temperature. According to this figure, it seems possible to assume either a constant sub-cooling temperature or a linear relationship between the sub-cooling and condensation temperature in the model.

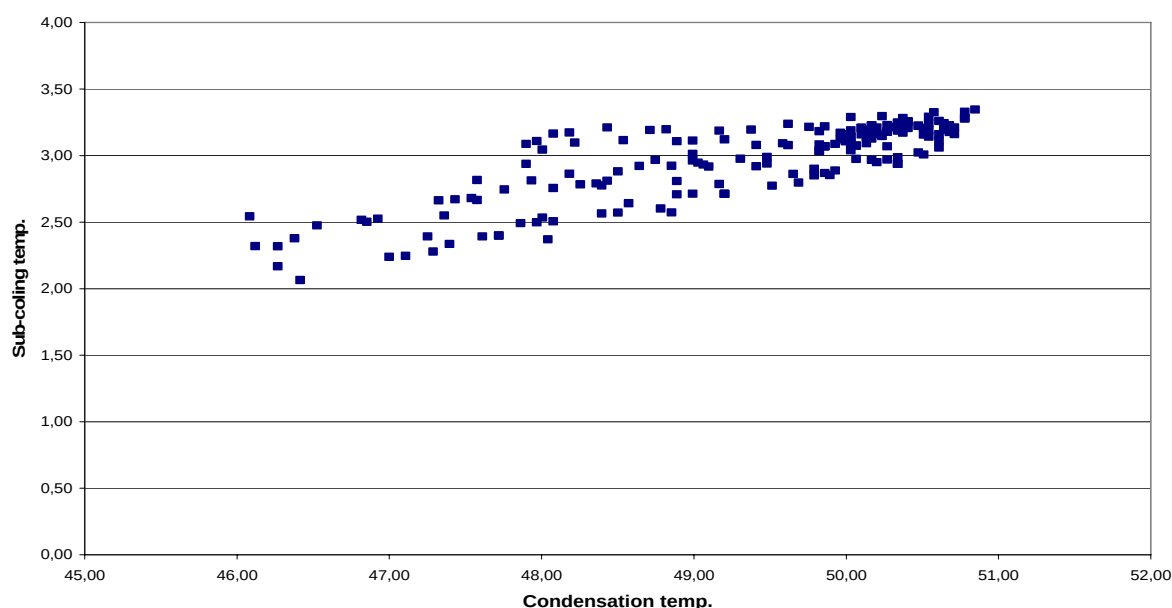


Figure 5: sub-cooling temperature vs. condensation temperature -experiment result

2.5 A parameter estimation model suitable for variable capacity case

This model uses minimum internally measured data and instead estimates parameters which are not easily accessible. Figure 6 shows the flowchart of the model in detail. The required measured data to feed the model can be:

- Load side temperature
- Source side temperature
- Heat transfer rate in evaporator
- Heat transfer rate in condenser ($\dot{Q}_{l_i_test}$)
- Compressor work ($\dot{E}_{i_test}$)
- Frequency
- Mass flow rates in both water and brine sides

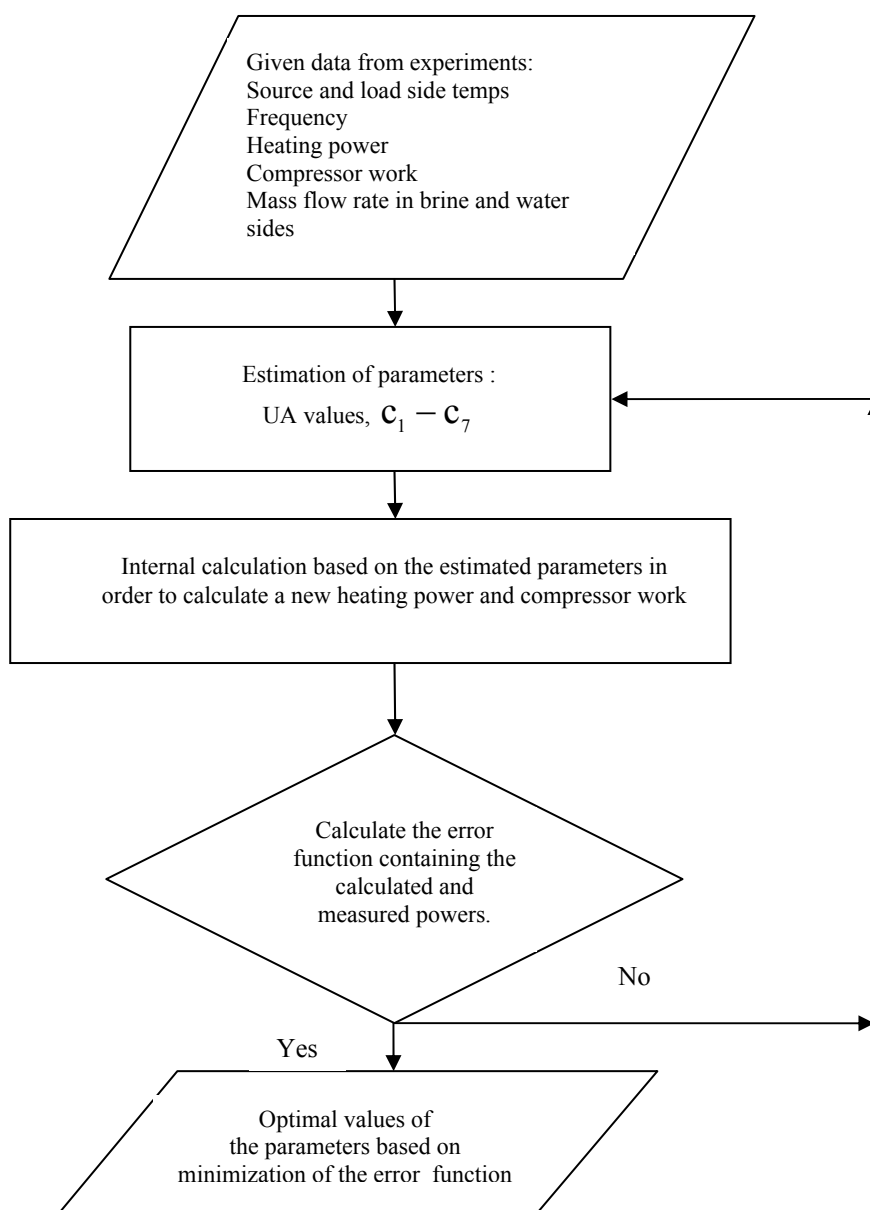


Figure 6: Flowchart of a parameter estimation model suitable for a heat pump with variable speed compressor

The data estimated by the model are:

- UA values in condenser and evaporator
- The correlation between superheat temperature and evaporation temperature:

$$T_{i_superheat} = c_1 \cdot T_{i_eva} + c_2 \quad \text{Eq. 1}$$

- The correlation between sub-cooling temperature and condensation temperature:

$$T_{i_sub-cooling} = c_3 \cdot T_{i_cond} + c_4 \quad \text{Eq. 2}$$

- The correlation between the total isentropic efficiency of the compressor and the frequency:

$$\eta_{i_isen,total} = c_5 \cdot f_i^2 + c_6 \cdot f_i + c_7 \quad \text{Eq. 3}$$

$$\dot{E}_{i_model} = \frac{\dot{E}_{i_isen}}{\eta_{i_isen,total}} \quad \text{Eq. 4}$$

Where,

f_i = frequency, HZ

$\eta_{i_isen,total}$ = Total isentropic efficiency

$\dot{E}_{i_isen}$ = isentropic power of compressor, kW

$\dot{E}_{i_model}$ = Power input to the compressor calculated via the model, kW

$c_1, c_2, c_3, c_4, c_5, c_6, c_7$ = The coefficients found by the model

Accordingly, the power input to the compressor and condenser heat transfer rate are calculated at each operating point according to both given and estimated data; then the error summation, err_{total} , is minimized based on a genetic algorithm⁴ and consequently the optimum values for the estimated parameters are determined.

$$err_{total} = \sum_{i=1}^n \left[\frac{\dot{E}_{i_test} - \dot{E}_{i_model}}{\dot{E}_{i_test}} \right]^2 + \left[\frac{\dot{Q}_{l_i_test} - \dot{Q}_{l_i_model}}{Q_{l_i_test}} \right]^2 \quad \text{Eq. 5}$$

Obviously, the total isentropic efficiency of compressor is strongly dependent on the type of the compressor. For instance, for reciprocating compressors, the dead volume of the cylinders and pressure drops in the suction and discharge sides of compressors are the key factors in their volumetric efficiencies. On the contrary, in scroll compressors, the mass leakage and suction heating up of refrigerant play the most important role. Chen et al. (2000) mentions that the mass leakage in a scroll compressor is mostly through the gap between the bottom or the top plate and the scroll called "radial leakage" and also through a gap between the flanks of the two scrolls called tangential". Granryd(2002) shows that this leakage is a function of the pressure difference between discharge and suction sides. Winandy (2002) also concludes that the heating up of refrigerant suction gas in scroll

⁴ Genetic algorithm is a robust but slow optimization algorithm which should be considered when the Direct Search and Variable Metric methods have failed and you are prepared to wait for calculations to reveal the true optimum point.

compressors, another important parameter in scroll compressor efficiency, is mainly and highly affected by the pressure ratio such that as the pressure ratio increases, the heat-up increases as well; so development of this model can yield the correlation between these parameters in different types of compressors.

2.6 The model validation

The model is validated against tests results (figure 7). The tested heat pump unit is of the ground source type with a variable speed compressor serving a typical single family house in Sweden. It provides heating water for both radiator and floor heating system and also domestic hot water. Table 2 presents the component specification of the unit. The heating capacity of the unit varies between 3-10 kW according to the heat demand of the building. Figure 8 depicts the scheme of the system.

Table 2; component list for the investigated variable speed heat pump unit

Heat pump component	Model name
compressor	Copeland Scroll ZR34K3E-TF5-3~220V
Condenser	Brazed plate heat exchanger B25-30L/L
Evaporator	Brazed plate heat exchanger B80-40L/L
Expansion valve	Honeywell thermostatic expansion valve, TLEX 3,0 R134a
Variable speed AC drive	Vacon NXS
Refrigerant	R134a

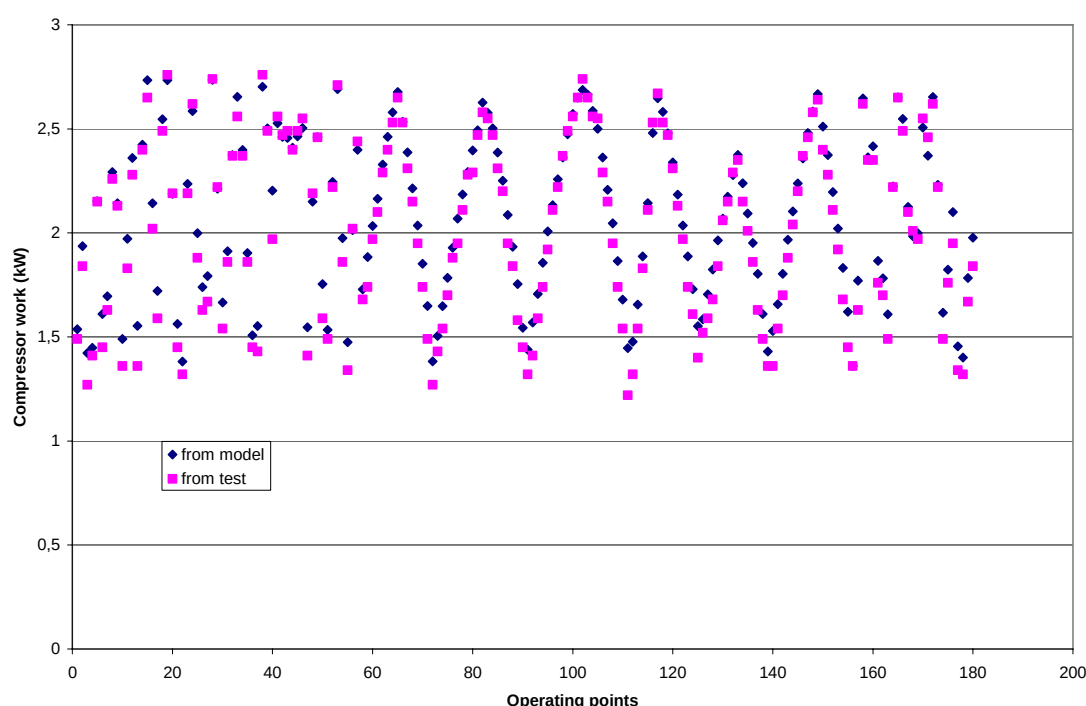


Figure 7: Compressor work (kW), model vs. test results

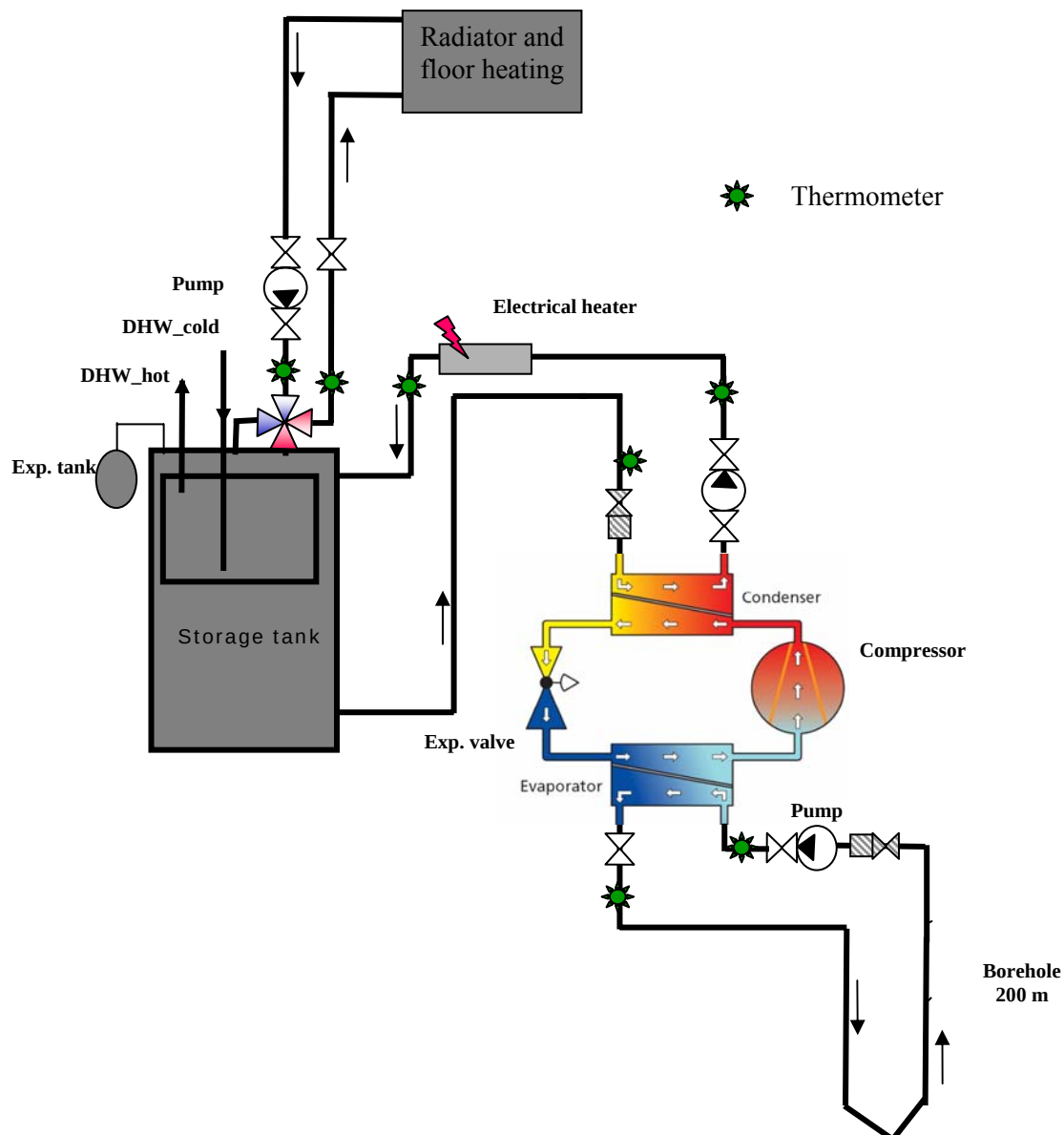


Figure 8: The scheme of the system tested for validation of the model

2.7 Conclusion

The present paper first discusses the significance of capacity control issue in heat pump systems. Then it describes some of the common limitations and obstacles in the investigations done so far. The inconsistency between the compared system components, the difficulties to achieve enough detailed measurements, and ignoring the importance of the system dynamics are some of the mentioned problems. Modelling and simulation of the whole system (covering all the system components) in a transient condition and use of the experimental data in order to validate the model seems to be the most promising way to advance the topic.

Then, the selection modelling approach, the first and most fundamental step in modelling, was accomplished. Due to the fact that the aim of the model is to obtain realistic heating capacity, compressor work and unit COP with minimum measured data, a parameter estimation model has been selected. The results show that this type of model can handle a sufficient level of detail without any need of complex measurement; so it fulfils the requirements in order to model the whole system.

In previous parameter estimation models developed for heat pump and refrigeration applications, certain assumptions may not be applicable for a heat pump system with variable speed compressors. The results of our test and simulation show that it is probably feasible to assume a constant UA value and apply it instead of a precise one from the test result. On the contrary, it is shown that the assumption of a constant superheat temperature is less appropriate. Furthermore, the experiments show that the sub-cooling temperature can be assumed either as a constant value or as the function of condensation temperature.

Moreover, the paper suggests a simulation procedure suitable for a heat pump unit with variable speed compressor. The outputs of the simulation can determine the compressor losses behaviour and other detailed parameters of the unit in various heat source and heat sink conditions. Consequently, this EES model can be linked to a dynamic simulation environment (in this case TRNSYS) to evaluate the performance of the whole system including building and heat source in a transient condition.

3 REFERENCES

- Bourdouxhe, J.P., M. Grodent, J. Lebrun, (1994). "A toolkit for primary HVAC system Energy Calculation-Part2: Reciprocating chiller model" *ASHRAE Transactions* Vol. **100**, part 2: 774-786.
- Claesson J., M. Forsen (2002). Capacity control of a domestic heat pump- Part 1- Performance of the heat pump and its components. Zero leakage-minimum charge Proceeding, Stockholm, Sweden.
- Chen Y., N. Halm, et al. (2000). A Comprehensive Model of Scroll Compressors, Part II: Overall Scroll Compressor Modeling. Purdue international Compressor Engineering Conference Purdue University, West Lafayette, IN.
- Fahlen P. (2004). Heat pumps in Hydronic heating systems-efficient solutions for space heating and domestic hot water heating (in Swedish), effsys.
- Granryd, E. (2002). Refrigerant property influence on Compressor efficiency, A simple model based on analysis of losses. Stockholm, KTH.
- Henderson H.I., D. Parker, Y.J. Huang (2000) Improved DOE-2's RESYS Routine: User-defined functions To Provide More Accurate Part Load Energy Use And Humidity Predictions. Proceeding of the ACEEE Summer Study On Energy Efficiency in Buildings, Pacific Grove, CA, US.
- Jin H., J.D. Spitler (2002) "A Parameter Estimation based model of Water-To-Water Heat Pumps for use in Energy Calculation Programs" *ASHRAE Transactions* Vol. 108, part 1:3-17.
- Karlsson F. (2007) Capacity control of residential heat pump heating system. Department of Energy and Environment. Göteborg, Chalmers University of Technology. Doctoral thesis.
- Qureshi T.Q., S.A. Tassou (1996). "Variable-speed capacity control in refrigeration systems." *Applied thermal engineering* Vol. 16, part 2:103-113.
- Sakellari D., M. Forsen, P. Lundqvist (2006). "Investigating control strategies for a domestic low-temperature heat pump heating system" *International Journal of Refrigeration* 29:547-555.
- Sheldrake T. (1991). "Introducing variable-speed drives." *Building Services*: 25-32.
- Zubair S.M, V. Bahel (1989) "Compressor capacity modulation schemes" *Heating, Piping, Air-conditioning*: 135-143.