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Dynamic Heat Process in a Climate Chamber

Master thesis in Sustainable Energy Systems

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Abstract

Heat pumping technology is commonly used for heating and cooling purposes within building services nowadays. It has quick response for improving the indoor climate with high heat to power ratio. SP* was the first accredited European institute for heat pump performace testing with a focus on measuring the Coefficient of Performance (COP). The testing is commonly performed by installing the heat pump in a climate chamber which can provide standard testing conditions.

In the energy technology department of SP there is a new climate chamber that has recently been used in a research project to evaluate the performance of two air-to-air heat pumps. The performance of the climate chamber is critical to the accuracy of the testing results. The objective of this study is to determine the thermal property of the climate chamber, develop a numerical model to describe the dynamic thermal process of the chamber and evaluate the testing results by simulating the heating process.

By transforming the chamber thermal model to an equivalent analog electrical circuit and solving this first order system, an equation set was derived to describe the chamber thermal process. Several measurements and computer calculations were performed to determine the optimal parameters for the model. Finally the model was integrated with Matlab GUI and developed as a programme with user interface.

Several heat pump testing cases were investigated with this model. The results show that for measurements without large power variation and defrosting cycles the COP values from the Calorimeter test method and the simulations are very close. However, for measurements with large power variation or defrosting cycles there is a difference between these two results. This is mainly derives from the dynamic heat process where heat storage and heat loss influence the heat balance calculation. For defrosting process, the model can recreate the heating capacities reflecting real heat pump running condition.

Another utilization of the model is to analyze upgrade scenarios of the climate chamber. The chamber size is the most critical factor and should be kept small besides the necessary operation space. An increase of the thickness of the insulation layer can also improve the testing quality.

Further effort is suggested to expand the model to other climate chambers and real buildings. By combining the model with climate control systems, it could also improve the control quality of the climate chamber.

Keywords: climate chamber, thermal simulation, heat pump testing, defrosting

* SP, Technical Research Institute of Sweden

Foreword

This Master Thesis is a mandatory part of the Master Program Sustainable Energy Systems at Chalmers University of Technology. The project has been carried out in SP Technical Research Institute of Sweden, Borås. The study was done between February and June 2011.

I would like to give my sincere appreciation to my supervisor Ola Gustafsson and examiner Per Fahlén for their dedicated supervision during my master thesis work. I would also give my thanks to Zelin Li, Aurélie Jactard and all the co-worker in SP for the help and joyful time during the project.

Finally I would like to thank my parents for their supports and encouragement in completing my Master study.

Borås, June 2011

Lei Zou

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Symbols and abbreviations

P	*Power; W*
P_{heat}	Heating capacity of heat pump
P_{in}	Heating/cooling load inside the chamber
t	*Temperature; ^{o}C*
t_{inmea}	Measured chamber inside temperature
t_{in}	Simulated chamber inside temperature
$t_{in\infty}$	Stable chamber inside temperature
t_{amb}	Ambient temperature
t_{wi}	Chamber envelope inside temperature
t_{wo}	Chamber envelope outside temperature
$\dot{t}_{in}$	Transient change of chamber inside temperature
$\dot{t}_{wi}$	Transient change of chamber envelope outside temperature
$\dot{t}_{wo}$	Transient change of chamber envelope inside temperature
R	*Thermal resistance; $10^{-3}K/W$*
R_{tot}	Overall Thermal resistance of chamber envelope
R_{wall}	Middle layer thermal resistance of chamber envelope
R_{in}	Inside layer thermal resistance of chamber envelope
R_{out}	Outside layer thermal resistance of chamber envelope
C	*Thermal capacitance; kJ/K*
C_{air}	Air capacitance
C_{tot}	Overall thermal capacitance of chamber envelope
C_{w1}	Thermal capacitance of outer part of chamber envelope
C_{w2}	Thermal capacitance of inner part of chamber envelope
Φ	Heat flux; *W*
α	Heat transfer coefficient
u	Thermal transmittance;
A	Area; *m^2*
d	Thickness of chamber envelope; *cm*
λ	Thermal conductivity; *W/(m·K)*
τ	Time; *hour*
τ_c	Time constant; *hour*
COP	Coefficient of performance

1 Introduction

1.1 Background

In Sweden about 60 % of the residential energy use is for space heating, and 40 % of the space heating is generated by electricity-based equipment such as heat pumps (Unander, 2004). As energy and environmental issues become more important for the future development, analysis and optimization of the performance of residential heating equipment appears to be an essential task. One of SP's activities is testing heat pumps. The main purpose is to measure the energy performance (COP) at different running conditions where both temperature and heat load are varied. The temperature is controlled by installing the heat pump in climate chamber.

In the energy technology department of SP there is a new chamber that recently has been used in a research project to evaluate the performance of two air-to-air heat pumps. The performance of the climate chamber is critical for the accuracy of the testing results. The uncertainty level of the climate chamber needs to be investigated.

1.2 Aim and Scope

The aim of this study is to develop a numerical model that describes the thermal properties of the new climate chamber. To investigate the testing quality of the climate chamber, simulation for the testing process needed to be carried out. The model should be used as a tool for climate chamber improvement analysis and suggestions. This study seeks to answer the following questions:

- What are the thermal properties of the climate chamber?
- What is the uncertainty of the model?
- How well do the test result (Calorimeter method) agree with the simulation?
- How does the heat capacity of the heat pump changes during defrosting process?
- How should the chamber be upgraded to make it better for heat pump testing?

1.3 Boundaries

When building the model for the chamber, the actual performance of the climate chamber is hard to determine. Therefore the modelling validation was based on measurements that were carried out during this study. The chamber is built on a concrete slab floor so the concrete temperature may vary for different periods of the year. This may lead to a small influence on the accuracy of the model. Here the ground temperature is assumed to be just the same as the surrounding air temperature.

For the chamber temperature measurements, it is assumed that the air is well mixed inside the chamber, as the fan of the cooling/heating equipment provides strong ventilation.

For the real heat pump data analysis, there is no accurate short term heating capacity measurement available for the testing process. The comparison is only between the testing method and model simulation. The uncertainty of the testing method will influence the results.

1.4 Method

This chapter describes the methods that have been chosen to conduct the study and to solve the questions in the "Aim and Scope" section.

1.4.1 Literature review

A literature review on the modeling of real building heating/cooling conditions is carried out in order to gain the knowledge of modeling theory, strategy and scale. The current methods for building heat flow calculations are finite difference method, response factor method, conduction transfer function method (Unander, 2004) and simplified thermal model method (Gilles Fraisse, 2002). The simple thermal model method is chosen in this study since it is effective and efficient enough (B. Yu, 2004) and also intuitive for the chamber heat flow simulation.

1.4.2 Simulation strategy

The simulation in this study is based on formulating the thermal model of the climate chamber, converting it to an equivalent analog circuit and deriving an equation set that describes the thermal behaviour of the climate chamber. The model is developed as a time domain simulation in Matlab.

The climate chamber is a sealed space so no mass exchange but only heat exchange occurs with the surroundings. A heating/cooling power input to the chamber will lead to heat flow between the chamber inside air and its envelope, as well as chamber envelope and the surrounding air. The heating process is dependent on the initial condition of the chamber, power input, ambient temperature and chamber thermal properties. The simulation describes the dynamic response of the chamber inside temperature to the variation of heating/cooling power and ambient temperature.

For a simple thermal model, resistances and capacitances are used to represent the thermal conductivity and heat storage, an R-C analog circuit describes the heat flow system of the chamber. Then by solving the R-C circuit, a mathematical equation set is derived to describe the model. The equation set uses heating/cooling power, ambient temperature as inputs. With the initial condition and proper parameters for the equation, the heating process can be solved to get the transient chamber inside air temperature.

1.4.3 Measurements

Proper parameters are critical for the accuracy of the model. For real building simulation the heat transfer coefficient and heat storage coefficient can be looked up. For this climate chamber model, however, some of the parameters are needed to be determined based on measurements due to the fact that the dimensions and constructions have large influence on the thermal property of the climate chamber.

The general method of the measurements is to use a heater in the chamber as power input and distribute temperature sensors to measure the chamber and ambient temperatures. The heater is connected via a transformer and a power meter so the power input can be adjusted and recorded. Two kinds of measurements are performed. One is to use constant heating power in the chamber. The chamber inside temperature keeps increasing until it reaches the balance temperature, i.e. heat balance between the heating power and heat loss through the chamber envelope. The other measurement is to use a variable heater power input to acquire the temperature response character of the climate chamber. By combining these temperature profiles with some computer calculations, the model parameters can be estimated and optimized.

1.4.4 Case study

1.4.4.1 Heat pump testing

The air-to-air heat pump testing was performed with the Calorimeter method within the climate chamber. Several test cases were investigated by simulation to compare the testing results. The studied cases include both stable heat pump working cycles and defrosting cycles.

For each test case, the measured chamber inside temperature was processed by the model to get the heat pump heating capacities during the testing period. The COP value was calculated from the heating capacities and the heat pump power consumption for the whole testing period. The COP obtained from the simulation is compared with the COP value from the Calorimeter method.

When the heat pump works in the defrosting mode, there is a large heating capacity variation and this may not be accurately observed by the Calorimeter method due to the high thermal inertia of this climate chamber. Therefore some investigation was carried out for this special working cycle. The heating capacities were obtained from the model simulation by processing the measured temperatures, with the concerning about the heat pump working principles and the measured power consumptions. The heating capacities during defrosting cycles were compared with the results from the Calorimeter method to find out the difference and possible reasons. The COP values from simulation and Calorimeter measurement were also compared.

1.4.4.2 Upgrade scenario

The thermal performance of the climate chamber will influence the testing results most of the time. Therefore, an upgrade or reconstruction of a better climate chamber may improve the testing quality. Several climate chamber upgrade scenarios were studied by the model simulation to find out the possible critical factors to improve the climate chamber.

The upgrade scenarios include different improvement aspects such as the insulation material selection, envelope thickness and chamber size. By changing the parameters of the model these upgrade options can be applied and simulated under the same testing condition. Then several thermal performance simulations were compared and the comparisons include overall heat loss, time constant and response time for power variation. The results from the comparisons can provide design suggestions for future chamber upgrading and new climate chamber constructions.

2 Theory

This chapter introduces the theoretical background that relates to the study. A climate chamber is used to perform heat pump testing with the Calorimeter method. The heat transfer process, the heat pump working principle and the Calorimeter method will be introduced here.

2.1 Heat Transfer

For a climate chamber, when there is a temperature difference between the inside and outside of the envelope, there will be a heat flow through the envelope. For each individual surface of the climate chamber, as the side length is much greater than the thickness, the heat transfer could be simplified as one-dimensional large plate heat transfer process. The heat flux through the envelope is calculated as: t_{w1}

$$\emptyset = A \cdot u \cdot (t_{w1} - t_{w2}) \qquad (2.1)$$

Where $\emptyset$ is the heat flux, A is the surface area, u is called the thermal transmittance, t_{w1} and t_{w2} are the surface temperatures, as illustrated in Figure 1.

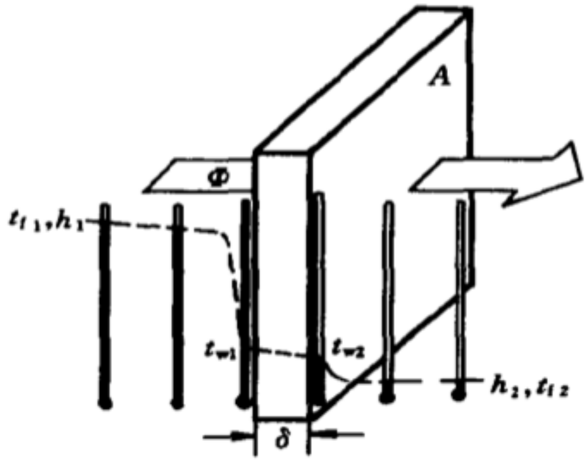


Figure 1. Heat transfer process through a large plate

It is important to determine the proper heat transfer coefficient k when calculating heat flux. The heat transfer coefficient depends on both the thermal property of the large plate and the properties of the fluids involved in the heat transfer process. The heat transfer coefficient includes the plate's heat conductivity λ and inside and outside heat transfer coefficient h_1 and h_2 respectively. Under some condition it is convenient to use the reciprocal value of k in the heat flux calculation. This is called the heat resistance R. Therefore the thermal resistance is present as:

$$R = \frac{1}{\alpha_1} + \frac{\delta}{\lambda} + \frac{1}{\alpha_2} \qquad (2.2)$$

When there is a heat transfer between the inside and outside of the climate chamber, some of the heat will be stored in the envelope. The heat storage effect depends on the heat flux, chamber dimension and the thermal capacitance of the climate chamber construction materials. For the heat transfer condition in Figure 1, if the thermal capacitance of the plate is C, the heat storage effect is present as:

$$\frac{d(t_{w1}-t_{w2})}{d\tau} = \frac{\Phi}{C} \qquad (2.3)$$

The heat transfer and heat storage effect should be considered simultaneously when dealing with transient thermal process calculation.

2.2 Heat pump system

The most common heat pump technology is the vapour compression process, which is used for various refrigerants and a large range of working capacity (Torbjörn, 2009). A basic heat pump comprises four main components: an evaporator, a compressor, a condenser and an expansion device.

Figure 2 shows the working principle for the vapour compression process. When the heat pump starts running, the evaporator absorbs heat (Q2) and the refrigerant is evaporated; then the saturated refrigerant vapour is sucked into the compressor. In the compressor both the pressure and the temperature of the refrigerant are elevated; in the condenser the refrigerant releases heat (Q1) and cools down to saturation status; after that the refrigerant passes through the expansion valve and becomes low temperature liquid/vapour mixture and then enters the evaporator for the next working cycle. This is the basic working process for a heat pump. The heat pump can function as heating device or cooling device depending on the requirement. For building heating purposes, the evaporator is set as outdoor unit and absorbs heat from a low temperature heat source, the condenser is set as the indoor unit that releases heat to heat up the indoor air.

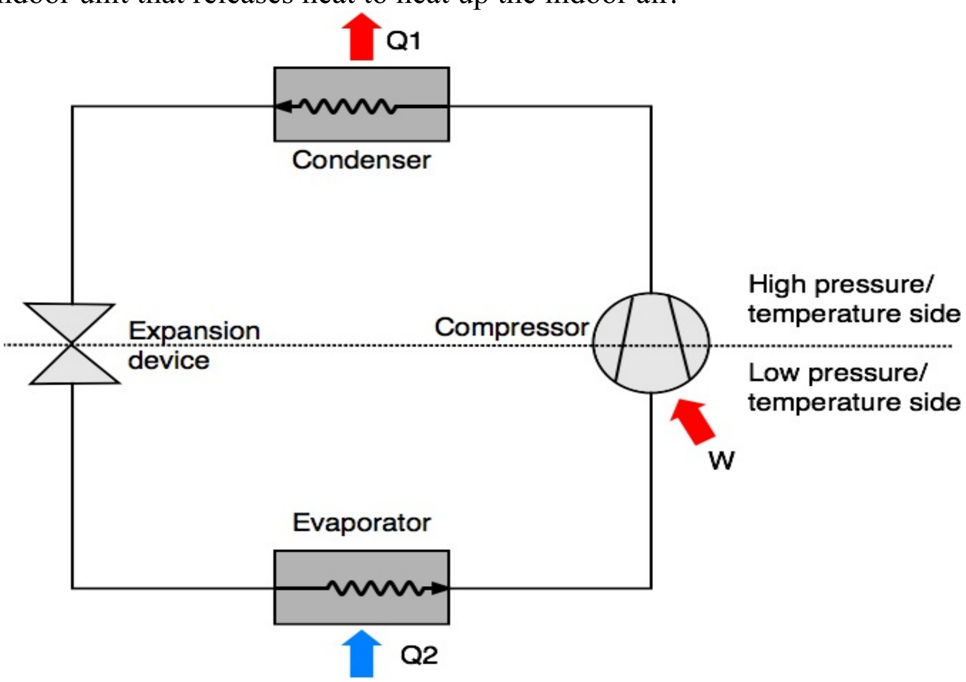


Figure 2. Vapour compression process

For a running heat pump the desired heating or cooling is achieved by providing work to the vapour compression process, mainly to the compressor. The ratio between the heating/cooling (Q) the heat pump delivered and the work (W) supplied to the process is called the coefficient of performance (COP). The coefficient of performance can therefore be expressed as:

$$COP = \frac{Q}{W} \tag{2.4}$$

2.3 Calorimeter method

Several methods are presently used to determine the COP of a heat pump by laboratory testing or field testing. The Calorimeter method is a commonly used laboratory test method and was performed during this study.

The heating capacity of free-blowing indoor units is difficult to measure directly, therefore Calorimeter method uses an energy balance to obtain the heating capacity of the heat pump. The testing is performed in a climate chamber with cooling control system. The indoor unit of the heat pump is installed in the climate chamber and the equipment set up is showed in Figure 3. During the testing the heating/cooling system of the climate chamber will adjust and maintain the climate chamber inside space at a certain condition. Considering of the dynamic process a minimum testing duration is needed to achieve a stable condition. Then based on the energy balance, the heating capacity is achieved from:

$$P_{heat} = P_{cool} + P_{loss} - P_{fan} \tag{2.5}$$

The cooling capacity is obtained from the measurement data of the cooling device; the heat loss through the envelope is calculated from the measurement climate chamber inside and outside temperature difference and the estimated UA value of the climate chamber. The power of the ventilation fan is recorded by a power meter.

The Calorimeter method provides accurate COP values for long term testing when the stable condition is well achieved.

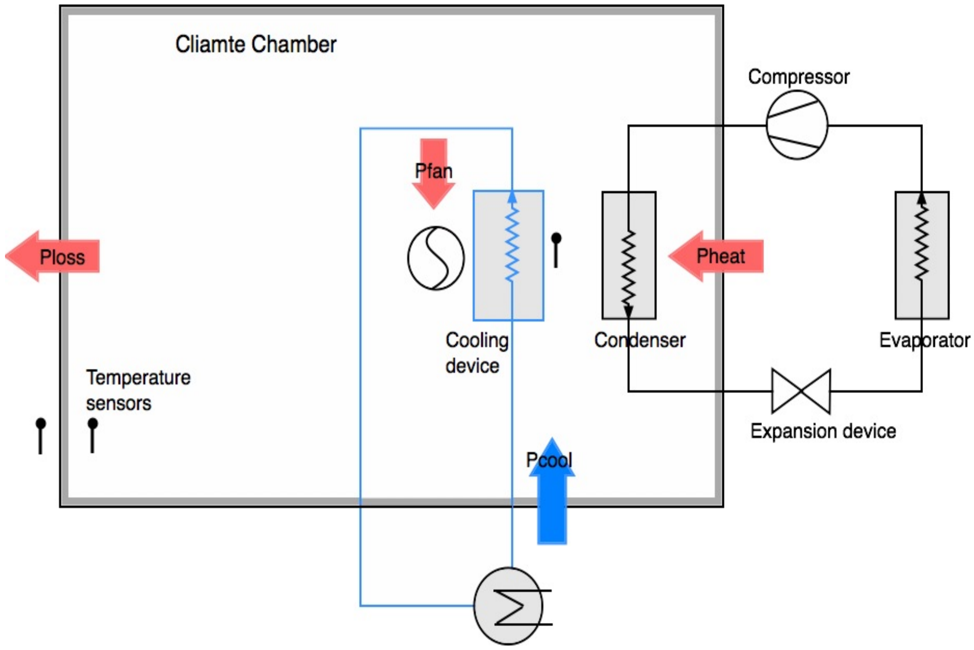


Figure 3. Calorimeter method equipment set up

3 Numerical Simulation

Based on the simulation strategy mentioned in the Method chapter (1.4), the detail procedures of the climate chamber simulation are described here.

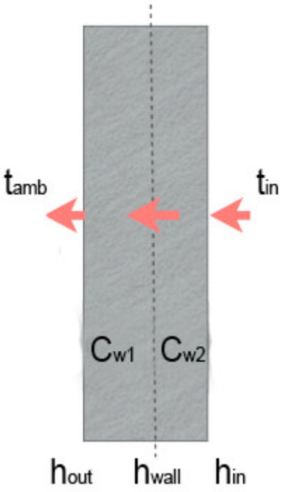
3.1 Modelling

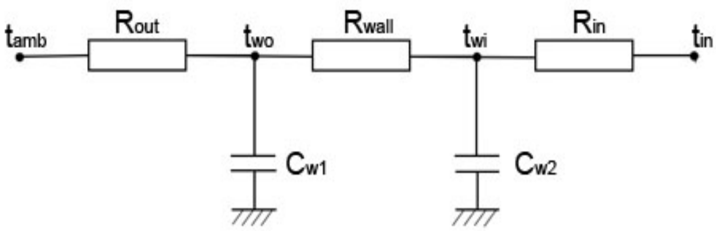
The climate chamber model is developed with mathematical equations that describe the thermal process of the climate chamber and solve the equations to simulate the transient thermal conditions.

To model the thermal process of the climate chamber, the heat flow process for a single wall of the chamber envelope was modelling first, as in Figure 4 (a). Since the height of the wall is much larger than the thickness, the heat flow through the wall could be seen as one dimensional heat transfer problem, i.e. heat transfer is only occurs in the horizontal direction showed as in Figure 4 (a). The heat flow value depends on the temperature difference and the thermal resistance of the wall. Three thermal resistances were used to represent the inside and outside heat transfer coefficients and the thermal conductivity of the insulation layer, as h_{in}, h_{out} and h_{wall} respectively. On the other hand, some of the heat will store in the wall depending on the thermal capacitance of the construction material. To make the model accurate the wall was split into two layers so there were two thermal capacitances. The heat transfer system is similar to an analog circuit system. Therefore the single wall heat flow process was converted to an equivalent analog circuit as in Figure 4 (b). The resistances and capacitances represent the thermal resistances and capacitances of the wall.

The circuit in in Figure 4 (b) only shows one wall of the envelope and there are six of them to enclose the climate chamber. They can be seen as parallel connection of each individual circuit, illustrated in Figure 5. This circuit represents the whole envelope of the climate chamber.

The thermal inertia of the air inside the climate chamber and heating/cooling power input to the chamber should also be included in the model. By simplifying the envelope circuit and integral with the air thermal capacitance and power input the final equivalent circuit was drawn as in Figure 6. The circuit with 3 resistances and 3 capacitances can describe the dynamic thermal process of the climate chamber.





(a) (b)

Figure 4. The transformation from a multi-layer wall to a 3R2C model

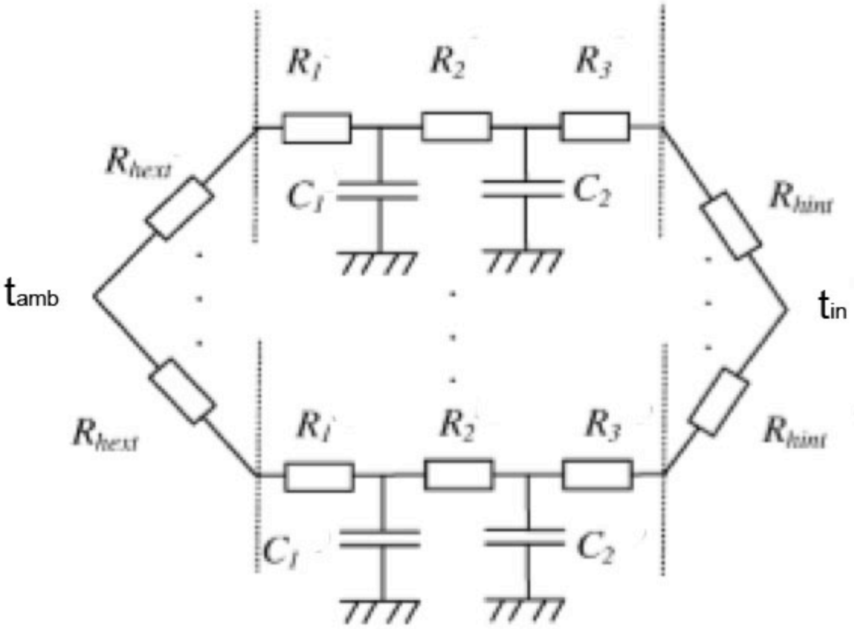


Figure 5. Aggregation of 6 single wall 3R2C circuit

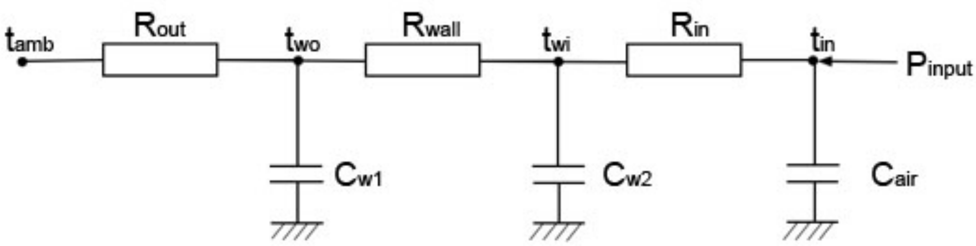


Figure 6. 3R3C analog circuit model for the climate chamber

In **Figure 6**, where:
R_{out}: the heat transfer coefficient of the outside surface of the chamber envelope,
R_{wall}: represents the thermal conductivity (resistance) of the chamber envelope,
R_{in}: the heat exchanger coefficient of the outside surface of the chamber envelope,
C_{w1}: the thermal capacitance of the outside part of the chamber envelope,
C_{w2}: the thermal capacitance of the inside part of the chamber envelope,
C_{air}: the thermal capacitance of the mass in the chamber (air and equipment)
t_{amb}: ambient temperature,
t_{wo}: chamber envelope outside surface temperature,
t_{wi}: chamber envelope inside surface temperature,
t_{in}: chamber inside average temperature,
P_{input}: heating/cooling load inside the chamber.

The circuit was transformed to mathematical equations to prepare for numerical simulation. By using heat balance and the Bond graph method, a first order differential equation set was derived to describe the state variables at each node. For the final circuit model, the equation set is:

$$\begin{bmatrix} \dot{t}_{in} \\ \dot{t}_{wi} \\ \dot{t}_{wo} \end{bmatrix} = \begin{bmatrix} -\frac{1}{C_a R_i} & \frac{1}{C_a R_i} & 0 \\ \frac{1}{C_{w2} R_i} & -\frac{R_i + R_w}{C_{w2} R_i R_w} & \frac{1}{C_{w2} R_w} \\ 0 & \frac{1}{C_{w1} R_w} & -\frac{R_w + R_o}{C_{w1} R_w R_o} \end{bmatrix} \begin{bmatrix} t_{in} \\ t_{wi} \\ t_{wo} \end{bmatrix} + \begin{bmatrix} \frac{1}{C_a} & 0 \\ 0 & 0 \\ 0 & \frac{1}{C_{w1} R_o} \end{bmatrix} \begin{bmatrix} P \\ t_{amb} \end{bmatrix}$$

Here, the heating or cooling load and the ambient temperature [P, t_{amb}]’ are the input of the model. The temperatures [t_{in}, $t_{wi,}$ t_{wo}]’ are the output of the model, among which the chamber inside temperature t_{in} is the most interested result.
The determination of equation parameters of R, C values is discussed in the following section.

3.2 Model optimization

To make the model accurately represent the studied climate chamber, the R and C values should be specified. In this study the individual R and C values were determined by measurements and computer calculations.

3.2.1 Measurement Data collection and analysis

Two kinds of measurements were performed here and the uncertainty analysis for the measurements is discussed later. The chamber with dimensions and the testing equipment arrangement are shown in Figure 7 and Figure 8.

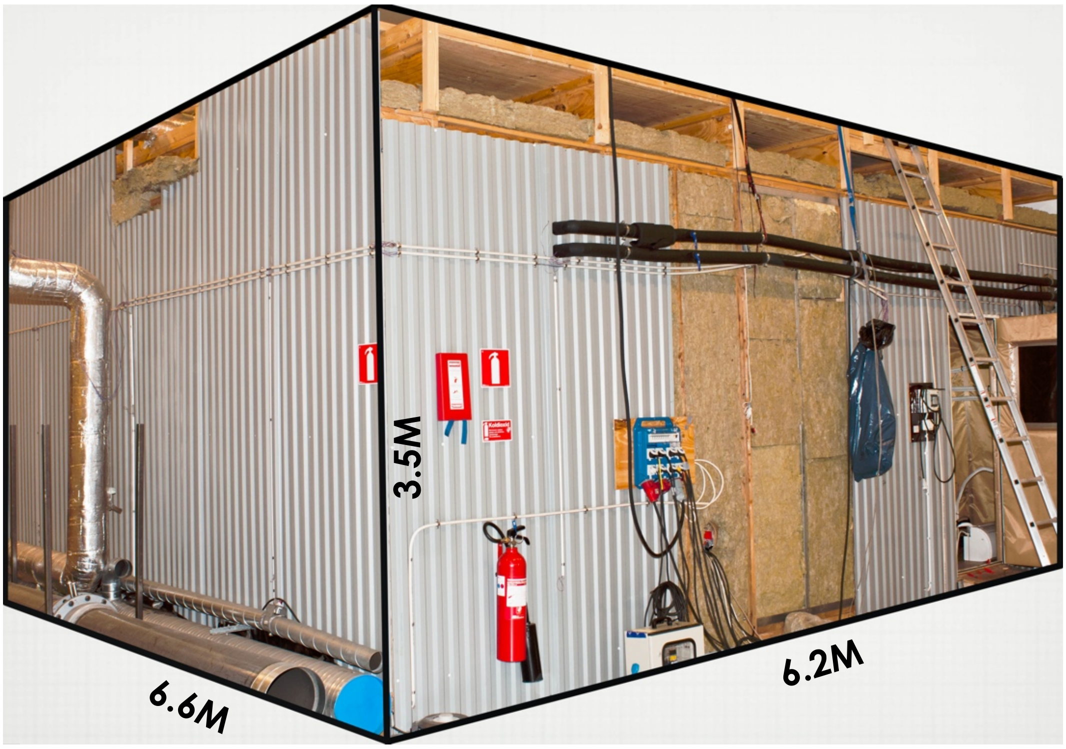


Figure 7. Climate chamber

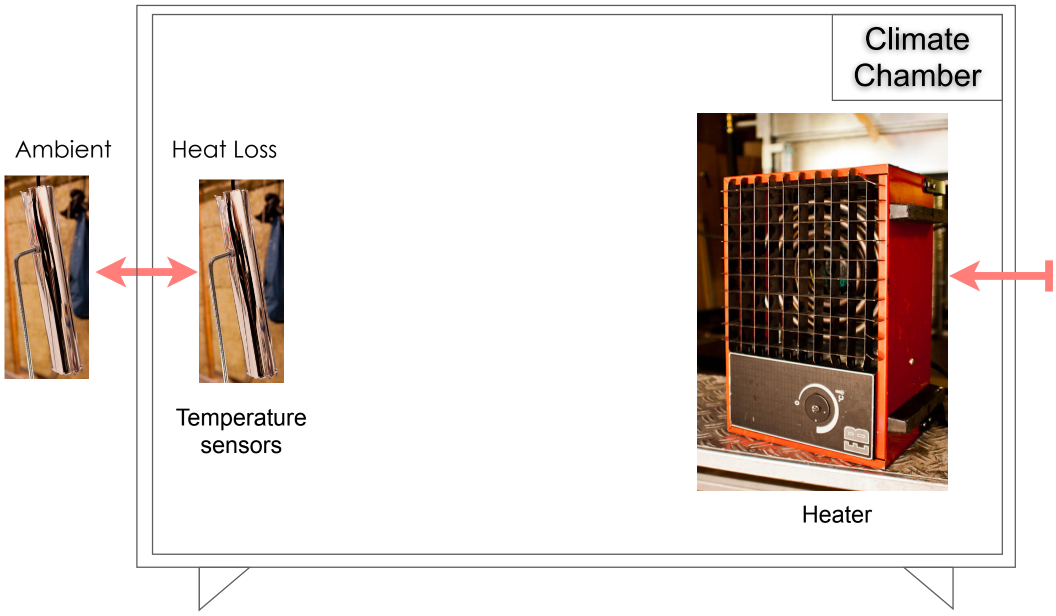


Figure 8. Equipment arrangement in the climate chamber

3.2.1.1 Measurement 1: stable heating power input

In this measurement the heater was placed close to the installing position of the heat pump in the climate chamber. The heater was connected with a transformer and power meter box. A constant power was supplied to the heater; in this case is 1000W. 14 temperature sensors were distributed to record the chamber inside temperature and ambient temperature. The chamber inside temperature t_{in} kept increasing until it reached the stable temperature. The temperature change during the measurement is showed in Figure 9.

Using the data from the stable period, where the heat balance between the heating power and heat loss from the envelope, the average overall heat transfer coefficient can be determined. For this chamber the overall heat transfer coefficient is 0.013 K/W, heat loss factor is 76.3 W/K. The whole recorded data was also used to examine how well the model matches the measurement in a long-term simulation.

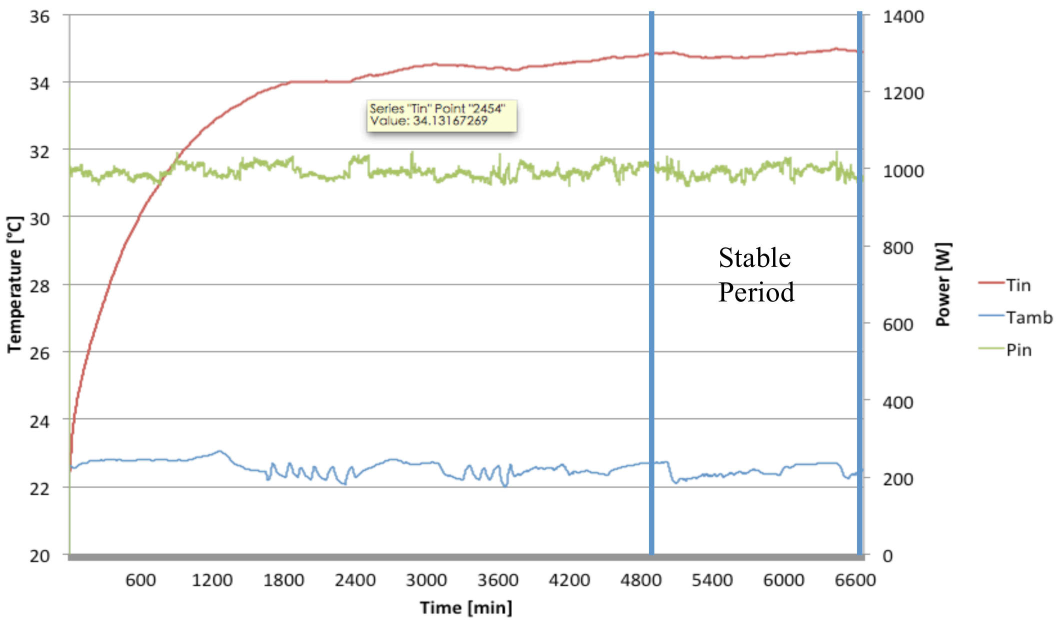


Figure 9. Measurement 1 result for stable power input to the climate chamber. The temperature increases and achieves stable condition.

3.2.1.2 Measurement 2: variable heating power input

In this measurement the heater was supplied with a variable power by manual controlling during the measurement. The same equipment arrangement was kept. The aim of this measurement was to decide how the chamber inside temperature responds to different power inputs. Figure 10 shows the measurement result. The power changes lead to the fluctuations of the climate chamber temperature.

The result can be used to examine how well the model matches the measurement when there is a variable power input.

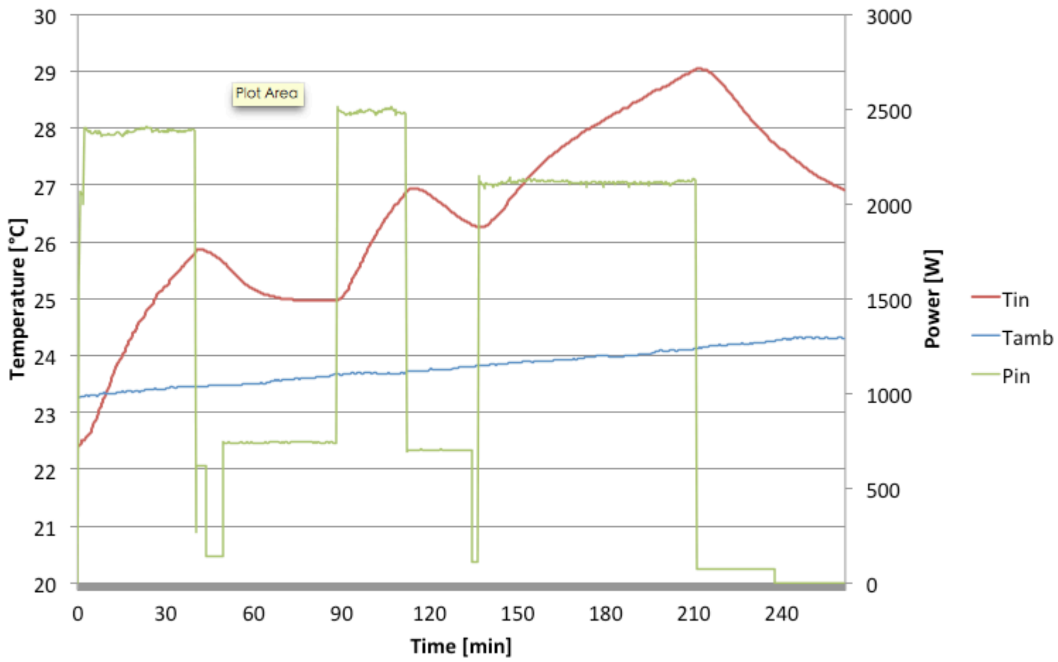


Figure 10. Measurement result for variable power input to the climate chamber. The temperature fluctuation follows the power change.

3.2.1.3 Uncertainty of the measurement

The uncertainty of the measurement is evaluated to assure the quality of the result. In the measurement two variables: temperature and power, are measured. The uncertainty of the power meter is small compared to the temperature sensors so it is neglected. For the temperature measurements, the uncertainty calculation process is based on BIPM (Bureau International des Poids et Mesures), which is accepted widely worldwide (Fahlén, 1994).

The evaluation standard takes two types of uncertainties into consideration, type A uncertainty is evaluated by statistical analysis and type B uncertainty is evaluated by means other than the statistical analysis (Fahlén, 1994). In this measurement type B uncertainty includes the calibration uncertainty and the instrumentation uncertainty of the PT100 sensors. The calibration uncertainty is neglected and the instrumentation uncertainty is 0.1°C according to the instruction from the supplier. After calibration this value could be considered as 0. For type A uncertainty, according to the evaluation standard, it is evaluated as:

$$u_x = s_{\bar{x}} = \frac{s_x}{\sqrt{n}}$$

In addition a coverage factor is used in order to obtain an expanded uncertainty. The coverage factor, k, is typically in the range 2 to 3, here k=2 is chosen to reach a confidence level of 95% (Fahlén, 1994). Then the overall uncertainty for the temperature is given by equation:

$$U_x = k \cdot u_x$$

The uncertainty of the heat loss factor K_{hl} is related to the power input and the temperature difference between the inside temperature and the ambient temperature of the climate chamber. Therefore the uncertainty of the heat loss factor is calculate as:

$$\frac{\Delta K_{hl}}{K_{hl}} = \frac{\Delta P_{in}}{P_{in}} - \frac{\Delta T_{in}}{T_{in} - T_{amb}} + \frac{\Delta T_{amb}}{T_{in} - T_{amb}}$$

$$\Delta K_{hl} = \frac{\Delta P_{in}}{T_{in} - T_{amb}} + \frac{P_{in}}{T_{in} - T_{amb}} \left(\frac{\Delta T_{in}}{T_{in} - T_{amb}} + \frac{\Delta T_{amb}}{T_{in} - T_{amb}} \right)$$

By processing the data of temperatures in the measurement the uncertainty is evaluated and the results are:

- The uncertainty of the temperature: ± 0.094 ^{o}C;
- The uncertainty of the heat loss factor: ± 0.24 W/K.

3.2.2 Parameter optimization

Three R and three C values are needed for the model. The parameters are determined by combining the measurements with calculations of time-domain simulations.

First the R and C values were estimated from the measurements and the property information of the chamber construction materials. The overall thermal transmittance of the chamber envelope was obtained from the measurements and the overall thermal capacitance was calculated by the properties of the insulation layer from the supplier's information. The total thermal transmittance is the effect of inside and outside surface convection heat transfer and the thermal conductivity of the insulation layer. The R and C values were estimated from the measurement results and information from the construction material supplier.

The computer optimization is necessary since the parameter estimation is not accurate enough for the model. The thermal conductivity cannot be calculated only by the means of the insulation's property since it is influenced by construction, compression/expansion, and intersection of each wall. Also the two thermal capacitances are not equal to each other as the different degree of involvement in the heat exchange process.

Therefore, to get the optimal parameters, computational loop and iteration for individual R and C values is applied. The principle of the parameter optimization is to choose the group of R and C values that make the simulation match the measurement result best. The process mainly involves three steps.

- Generate the group of R and C values, with the constraint of:

$$\begin{cases} R_{in}, R_{wall}, R_{out}, C_{w1}, C_{w2} > 0 \\ C_{total} = C_{w1} + C_{w2} \\ R_{total} = R_{in} + R_{w} + R_{out} \end{cases}$$

- Simulate with the parameter group;

- Calculate and record the standard deviation between the simulation and the measurement.

The optimal parameter group was determined by choosing the one with the minimum standard deviation. The detailed parameters comparison between the estimated parameters with optimal parameters is given in Table1.

Table 1. Comparison of estimated and optimal thermal parameters of the chamber model

Parameters of resistance, R (mK/W), and capacitance, C (kJ/K)								
	Rtot	Rout	Rwall	Rin	Ctot	Cw1	Cw2	Cair
Estimated	13.1	0.4	12.4	0.3	331	165	165	170
Optimal	13.1	0.7	10.4	2.0	331	43	288	111

3.3 Model validation

This part discusses how the model simulation matches the measurement. The climate chamber simulation with the optimal parameters was compared with the measurement result to examine the model quality and uncertainty.

First the simulation with constant power input is investigated. The measurement is mentioned in 3.2.1.1 as Measurement 1. The simulation and measurement t_{in} is plotted in Figure 11. In the first 150 hours the simulation temperature plot almost overlaps the measurement. Then there is gradually a difference between the two curves. The maximum difference is about 0.3 ^oC. The final stable temperature is the same for simulation and measurement result. The standard deviation for the temperature of this simulation is 0.10 ^oC.

Besides the constant power input measurement, a variable power input case is studied, which is the measurement 2 in 3.2.1.1. The simulation matches well with the measurement t_{in}. At inflection points the simulated t_{in} changes in advance to the measurement as in Figure 12. This may be because the temperature is not perfectly distributed and needs some time to mix. The maximum difference between the two curves is about 0.4^oC. The standard deviation for this variable power input case is 0.22 ^oC.

Accounting for all the performed measurements, the standard deviation between the model simulation and the measurement is 0.16 ^oC.

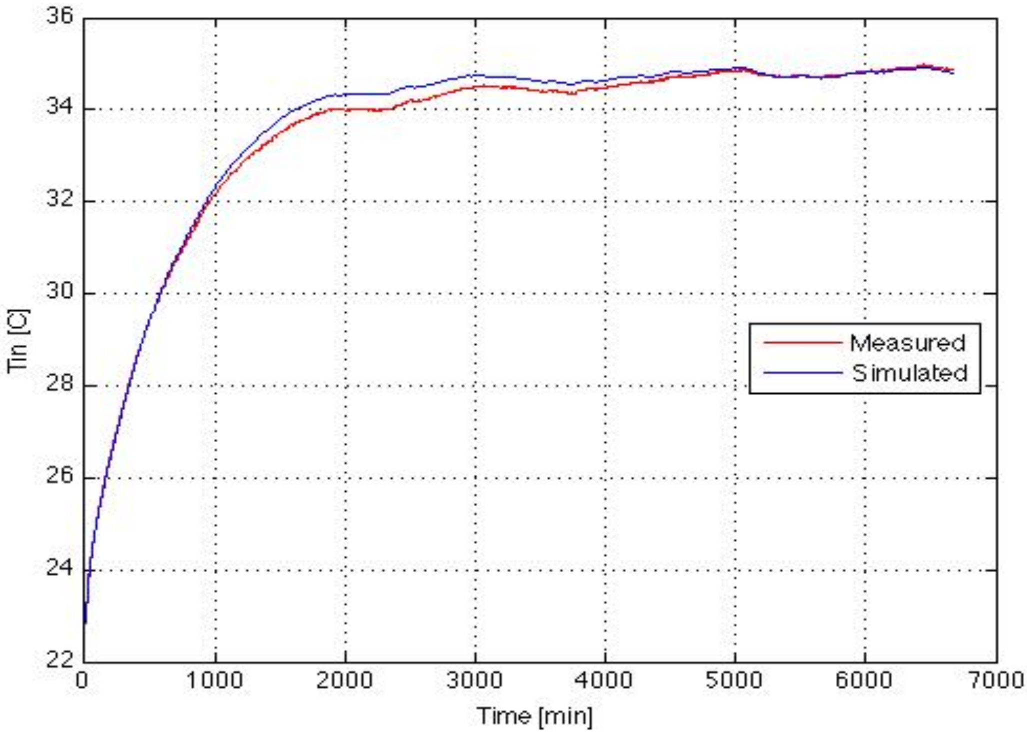


Figure 11. t_{in} change with constant heating power input. The simulated result agrees well with the measurement.

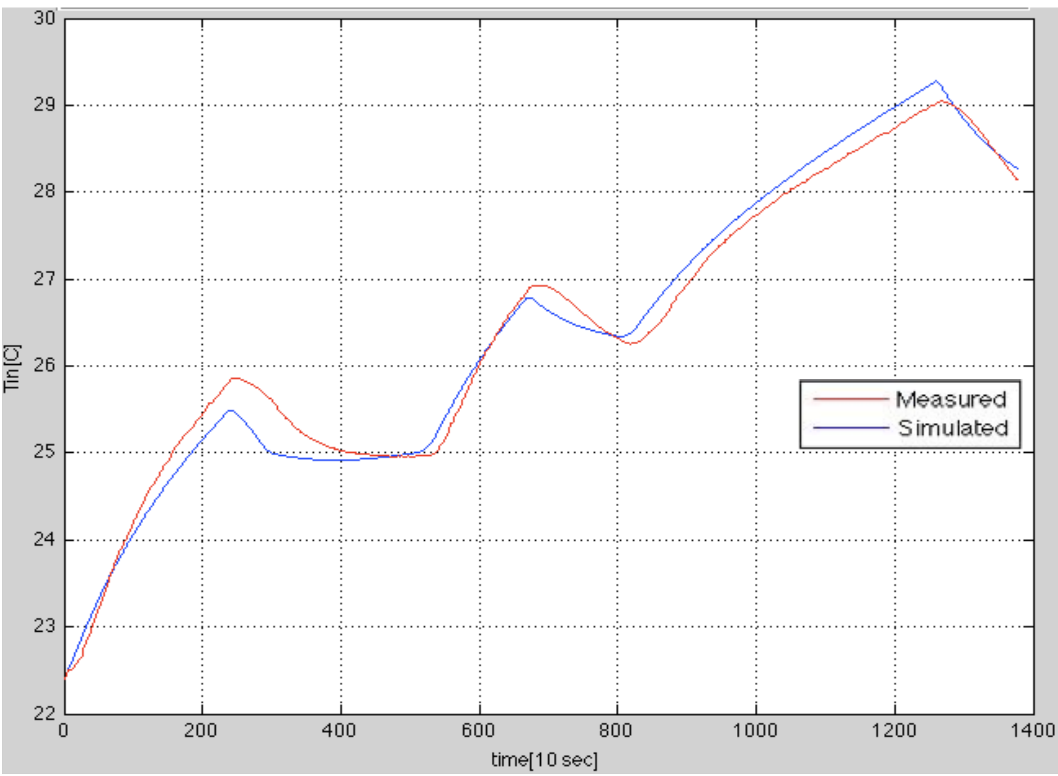


Figure 12. t_{in} change with variable heating power input. The simulation result follows the measurement with differences less than half a degree.

3.4 User interface development

The model can simulate chamber thermal process under different conditions and for different chambers. To make the simulation more intuitive and easy to use, a Graphic User Interface (GUI) programme is developed for this model. The main interface is shown in Figure 13. The left side of the panel is for data file selection, simulation time period, calibration and parameter setup. The right side of the panel displays the simulation plot, simulation errors compard with measurement and time to reach a certain temperature. There is also an option to save the simulation results as an Excel file with specified name.

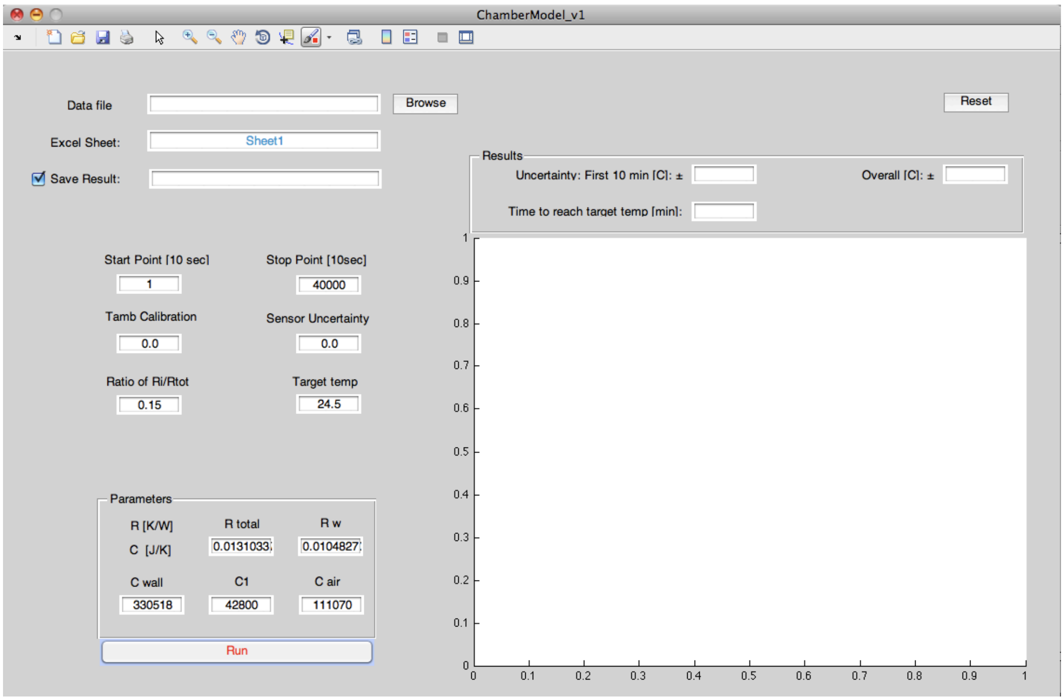


Figure 13. Matlab GUI for the model, with data input and output panels.

4 Model application and discussion

The model can simulate the transient chamber inside temperature with ambient temperature and heating/cooling power as input. Since it takes account for the heat loss and thermal inertia of the chamber, the unstable conditions become analyzable with the help of the model. Therefore for the short-term testing the results were evaluated with the model simulation. Especially when there were large power fluctuations during the testing, such as defrosting process. The temperature response of the climate chamber for the heating/cooling load change was also studied here. Besides the application for the present chamber property, alternatives to upgrade the climate chamber to improve the testing quality were investigated by adjusting the model parameters.

4.1 Simulation of test cases

The large volume of the climate chamber may influence the testing result due to the thermal inertia. Four testing cases were studied here to investigate the testing quality for different testing conditions. The first two cases have stable working loads while the last two have defrosting cycles during the testing period.

4.1.1 Testing cases with stable working load

The heating capacity of the heat pump was obtained by processing the measurement data and running the simulation. Since there is a limitation of this model that the heating/cooling power input to the chamber is needed to run the simulation, the heat pump capacities from the Calorimeter method are used to carry out the simulation. The main process was first using the Calorimeter testing result and the principle of defrosting process to estimate the heating capacity of the heat pump. Then the corresponding net power input to the chamber was derived. The simulated chamber inside air temperatures were obtained from the model simulation and then compared with the measured inside air temperature. If the temperature from the simulation matched the measured one, the estimated heating capacity was regarded as the right value. Else, if they did not match each other the heat pump heating capacity was adjusted until the right result was reached. The process is illustrated in Figure 14.

All these cases were processed with this method. In this section the simulated tests last 2 hours and 14 hours respectively.

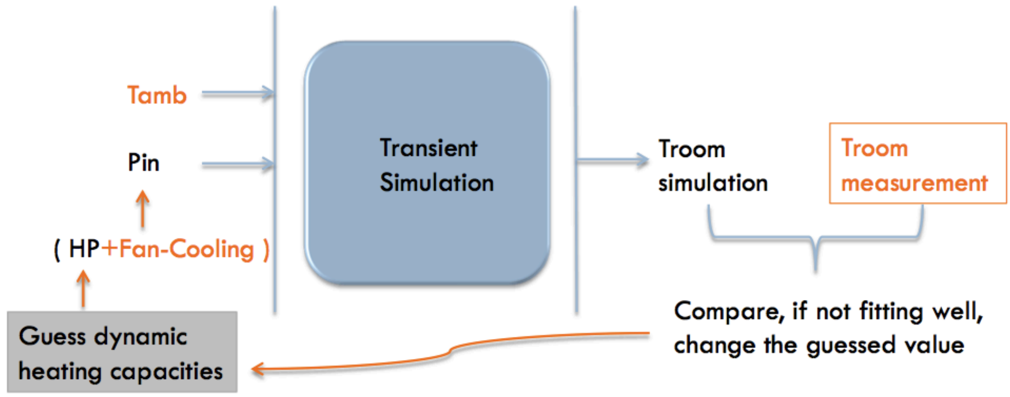


Figure 14. Heating capacity estimation process; use model simulation and measured climate chamber temperature to get heat pump heating capacity profile.

4.1.1.1 Case 1: 2 hours of simulated testing

A two hour testing period was chosen to be analysed with the model simulation. During this testing period there was no large heating condition change, therefore the climate chamber inside temperature was kept around 25 °C as shown in **Figure 16**. Under this condition the Calorimeter method gave a heat pump heating capacity with large fluctuations. This may be due to the calculation process including the cooling system and the cooling system having a periodically changing cooling capacity. The simulated heating capacity was relatively stable as shown by the blue plot in **Figure 15**.

The overall COP values calculated from simulation and Calorimeter method were very close for this two hour testing case.

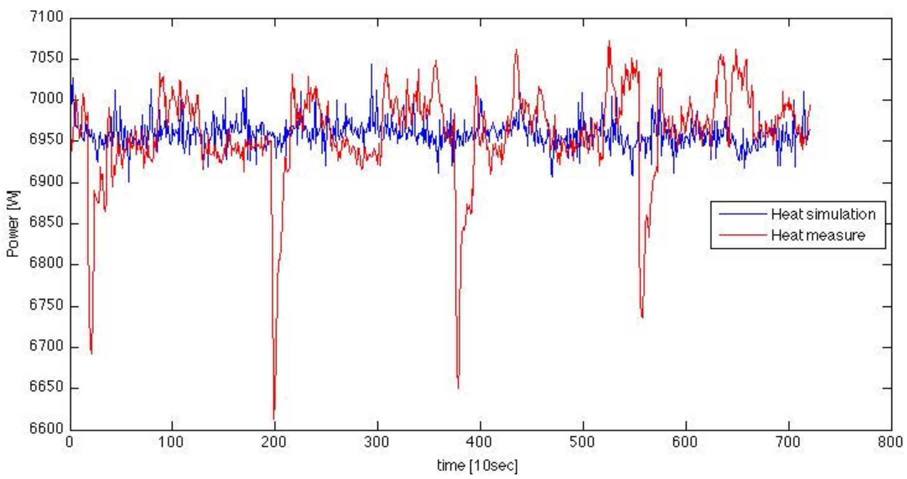


Figure 15. 2 hours heating capacity of the heat pump from simulation and Calorimeter method. The red one from Calorimeter method has larger fluctuations than the blue one from simulation.

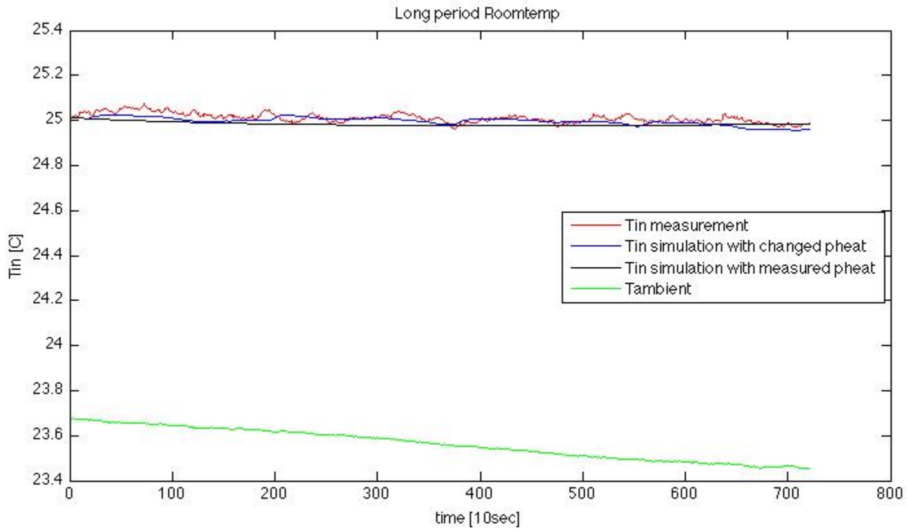


Figure 16. Climate chamber temperature during the testing; both the measured temperature and the simulated temperature are stable.

4.1.1.2 Case 2: 14 hours of simulated testing

A longer testing case that lasts 14 hours was analysed with the model simulation. The climate chamber temperature fluctuations were within 0.5 ^{o}C that means there was no large heating condition change during this testing. The Calorimeter method still gave a heating capacity with larger fluctuations than the simulated one. This may also be caused by the cooling system.

The simulated climate chamber temperature agrees well with the measured data. This is shown in **Figure 18** as the blue and red curves. Another climate chamber temperature profile was obtained by simulating the heating process with the heating capacity from Calorimeter method. This gave a stable temperature profile as the black plot in **Figure 18**, which was not match with the measured temperatures.

The COP values from simulation and Calorimeter method were very close for this 14 hour testing. Therefore, for the testing cases without large heating condition variation, the model simulation and Calorimeter method give similar overall COP values. However, the simulated heating capacities give climate chamber temperatures close to the measured temperatures. So for transient heat process analysis, the model will provide better accuracy.

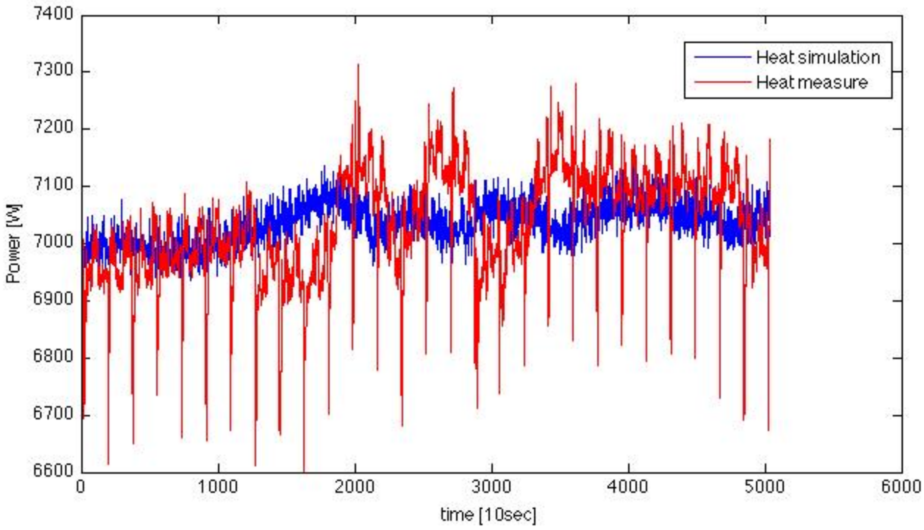


Figure 17. 14 hours heating capacity of the heat pump from simulation and Calorimeter method; the red one from Calorimeter method has larger fluctuation than the blue one from simulation.

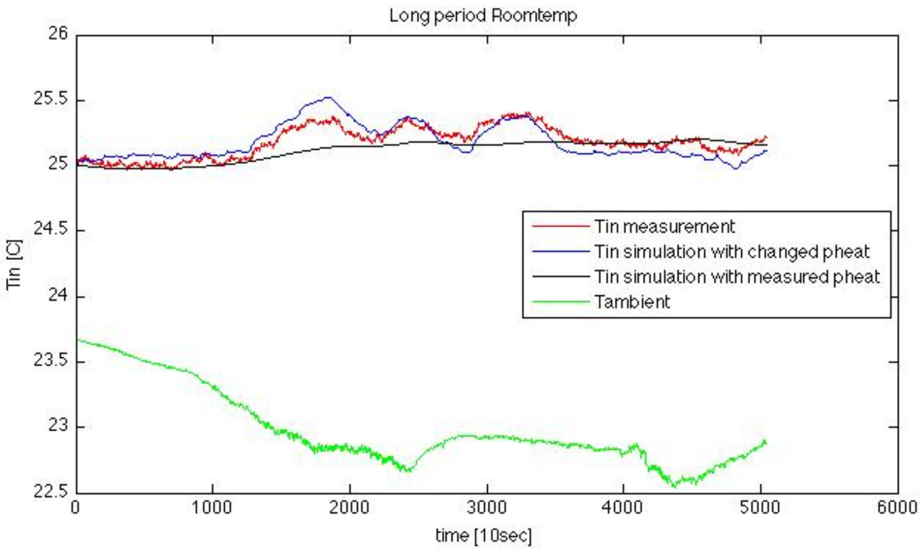


Figure 18. Climate chamber temperature during the testing; the simulated temperature is in agreement with the measured one.

4.1.2 Defrosting process analysis

The main heat pump testing methods include the Calorimeter method, the SP method, and the Climacheck method. When the heat pump testing includes defrosting, these methods may not observe the actual heating capacity change during the process due to the measurement instruments limitation and the thermal inertia of the climate chamber. The climate chamber model simulations were performed to recreate and analyze the defrosting process.

4.1.2.1 Case 1: without cooling control

In this case, during the testing process the cooling in the chamber was not shut down during defrosting since no cooling control was provided.

Figure 20

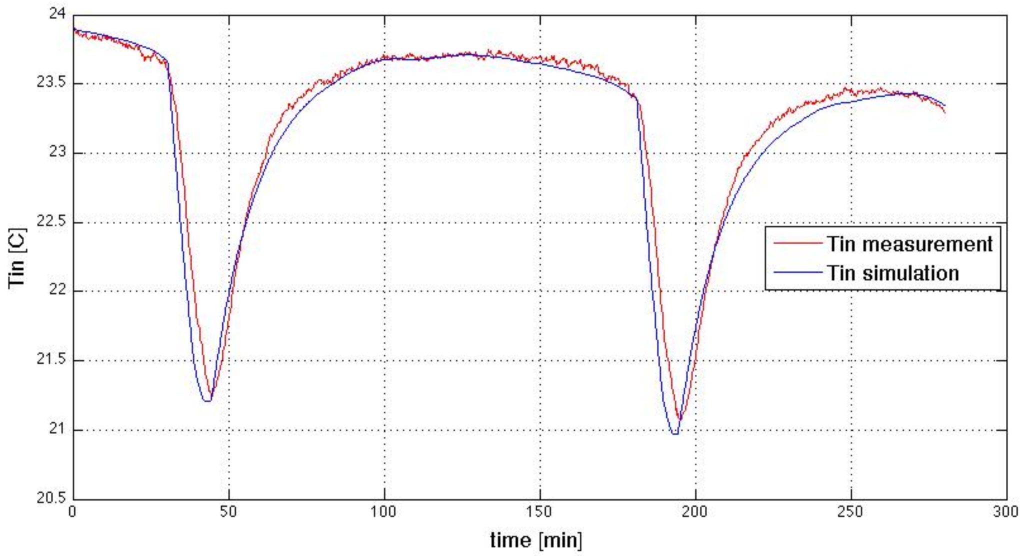


Figure 20. tin of defrosting process without cooling controlis the climate chamber temperature from the measurement (red plot) and the simulation (blue plot). The blue curve matched the red one well so the simulated heating capacity is close to the real value. Figure 19 shows the heating capacity from the simulation (blue plot) and from the Calorimeter method (red plot). The two troughs in the figure means two defrosting cycles. For the Calorimeter method the heating capacity did not go down too much and it took a long time to recover the peak load. This is due to the large thermal inertia that moderates the temperature change during defrosting. Since the model takes account for the thermal capacity during dynamic power change, the blue curve gives a result that better represents the actual heat pump capacity than does the red one. When the defrosting started, the heating capacity went down to zero immediately and then kept dropping below zero. After that the heating capacity gradually increased back to peak load. Then it kept the high working load until the next defrosting happened.

The COP values were different from the simulation and the Calorimeter method. The Calorimeter method gets the heating capacities based on a heat balance that not includes thermal capacitance. When there are defrosting cycles involved this heat balance may not be kept. The COP for the Calorimeter and simulation results is 2.85 and 2.74 respectively.

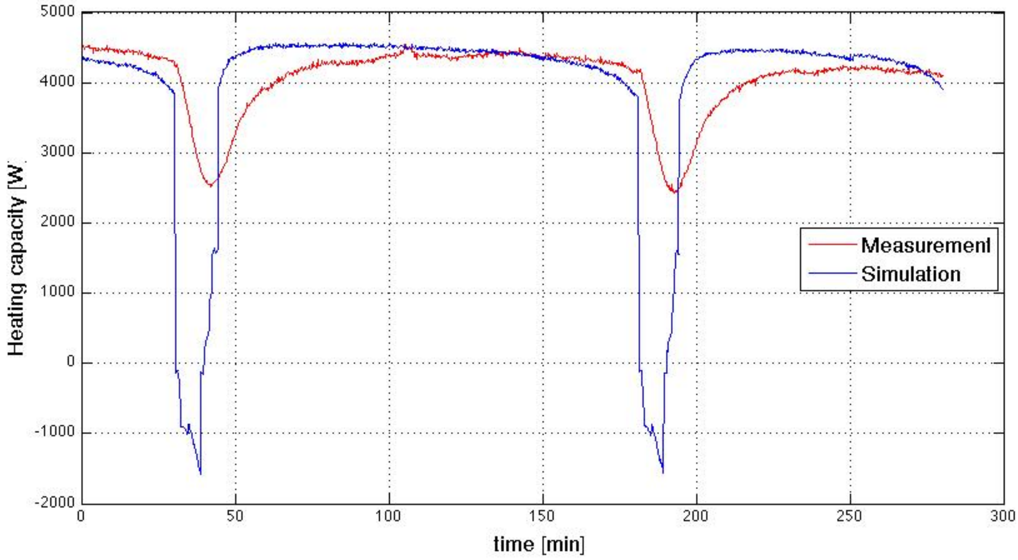


Figure 19. Heating capacities of defrosting process without cooling control. The heating capacity from the Calorimeter method only showed a small fluctuation; the simulation gave much larger changes during defrosting.

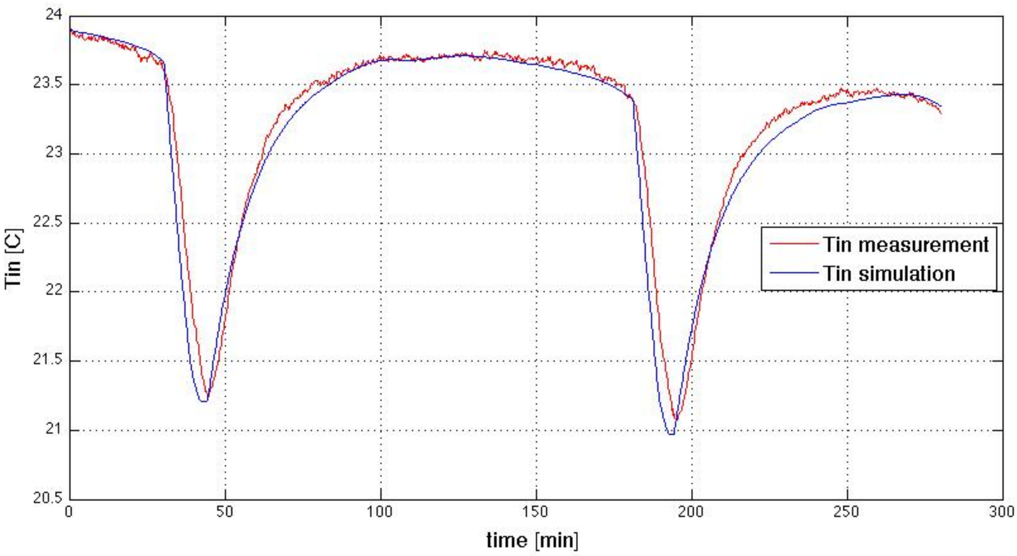


Figure 20. t_{in} of defrosting process without cooling control, with the simulated heat pump heating capacity profile. The climate chamber temperature from the model fit the measured temperature quite well.

4.1.2.2 Case 2: with cooling control

The testing case studied here was performed with a cooling control system. The cooling fan was shut down when the defrosting process started and the cooling recovered after defrosting was completed. With this control mechanism the heat balance was maintained better than the one without cooling control, but there are still some factors that may lead to the error of testing results. One factor is that the cooling fan is triggered by temperature sensors and therefore there is a lag for the start of the control. Another factor is after the cooling fan stops, the forced convection heat transfer decreases to almost zero immediately between the cooling pipes and surrounding air. However, there is still natural convection heat transfer. Since there is no strong ventilation within the chamber the cooling may happen locally and cannot be observed by the temperature sensors.

In this case a heat pump operates at full load with an outdoor air dry bulb temperature of 4 ^{o}C. The heating capacities from the Calorimeter method went down to very low values when defrosting started gradually and then recovered to full load after about 8 minutes. It reflects the defrosting process better than the case without cooling control because the heat balance was not broken so seriously during defrosting.

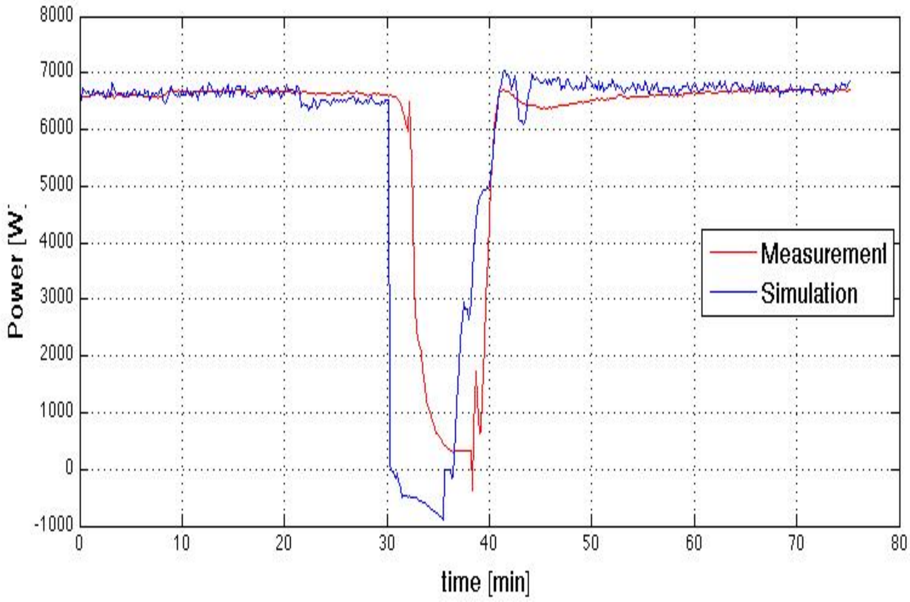


Figure 21. Heating capacities of the defrosting process with cooling control. The changing rate of the heating capacity of the simulation is different from the measured one.

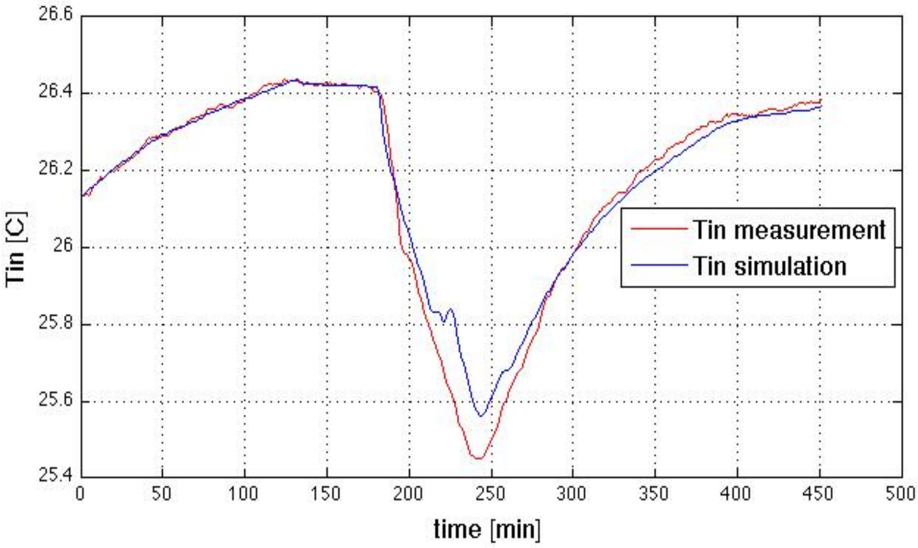


Figure 22. t_{in} of defrosting process with cooling control; the temperture from the simulation agree with the measurement

The COP value from the Calorimeter method was 2.33. Besides COP value, COP ratio is another number that is calculated from the heat pump testing. It is used to see the influence of defrosting process to the heat pump performance. COP ratio is defined as the overall COP value divided by the peak load period COP. However, in this case the COP ratio is 1.01, which gives an indication that the heat capacity profile is not so accurate. Since the model is used to get a better estimation of the heating capacity, a more accurate COP ratio is expected. So it also showed in this case, for the simulated result, the COP for the whole cycle is 2.28; the COP ratio is 0.985, which is less than 1.

4.2 Climate chamber response time

When a power change happens during the testing it takes some time for the climate chamber to reach a certain temperature or stable condition. The response time influences the testing quality of the climate chamber. The time constant and the time needed to reach the target temperature under certain condition is investigated with the model simulation.

4.2.1 Time constant

The time constant can represent how the climate chamber responds to a heating power step change. The rate at which the response (chamber temperature) reaches the final value (stable temperature) is determined by the time constant, τ_c. When $\tau = \tau_c$, the temperature reaches 63.2 % of its stable value, illustrated in Figure 23; when $t=3\tau$, Tin reaches 90% of $Tin\infty$; when $t=5\tau$, Tin reaches 99.3% of $Tin\infty$ (Lab, 2006).

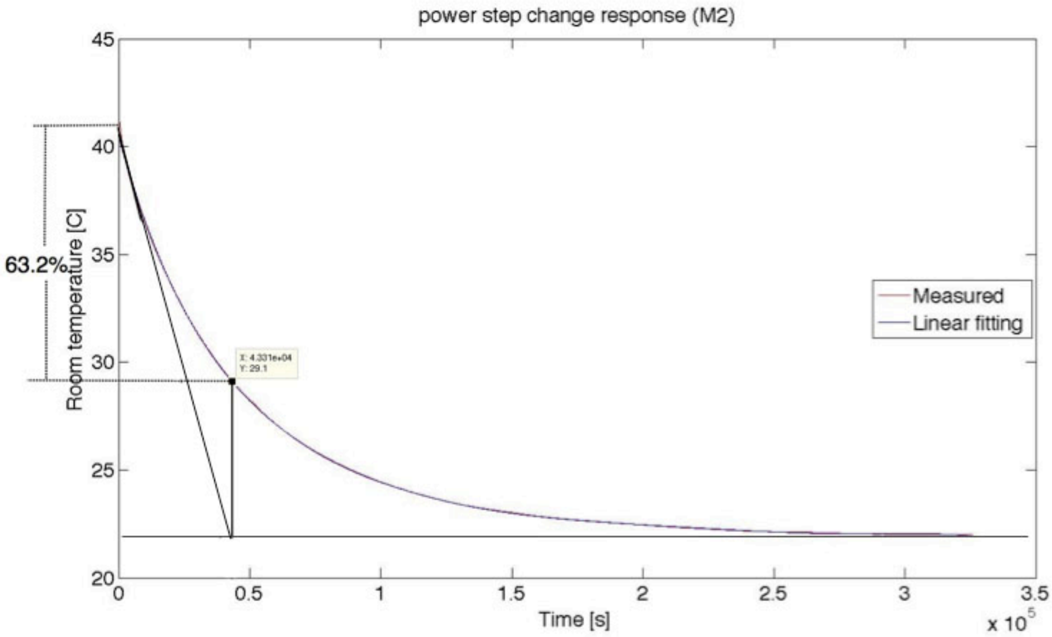


Figure 23. Time constant of the climate chamber. It takes a long time for the temperature to get stable. The duaration for the temperature to reach 63.2 % of the temperature difference is the time constant.

The time constant depends on the thermal property of the chamber and is independent of surrounding air temperatures and power input.

The time constant of this model is determined by the measured temperature and using a linear regression to this temperature (Lab, 2006). The result is τ_c =10.4 hours for this climate chamber. To reach 90 % of stable temperature 31.2 hours are needed. This is a long time and not so practical to wait in testing. Time constant is how the t_{in} responds to a fixed power change, while in a real testing condition the power is a variable controlled by the cooling equipment. Due to the climate chamber control system it takes less time to reach a certain temperature. So in the next section another type of response time is studied.

4.2.2 Reaching a certain temperature

The power fluctuation will lead to temperature changes during testing. How quickly a chamber can reach a certain temperature reflects the thermal property of the climate chamber. Shorter responding time means better heat pump testing quality a climate chamber can provide. Therefore how much time it needs for the chamber to reach a certain temperature is investigated here.

An arbitrary testing condition is set. This condition is used for investigating how much time it takes the chamber to reach the target temperature. The assumed testing condition is:

- The ambient temperature is constant, 22 ^oC;
- The initial temperature of the chamber is the same as the ambient, 22 ^oC;
- The power input to the chamber is kept as 1200 W;
- The target temperature is 24.5 ^oC.

Under this condition the time for the chamber to reach 24.5 ^{o}C is 91 minutes. This is a much shorter time than the time constant and it is practical to use as an indication of the climate chamber response time. The same condition is used in the next part to evaluate different chamber upgrade scenarios.

4.3 Climate chamber improvements

The thermal property of a climate chamber influences the quality of the testing results. The thermal property mainly depends on the size and shape of the chamber, the thickness and property of insulation material and airtightness. Before an upgrade of a climate chamber or construction of a new one, the influence of each factor on the time response should be taken into consideration.

This model is able to simulate the chamber with different properties. By changing the model parameters, different chamber time responses can be investigated. In this study three factors are considered: different insulation thermal conductivity, thickness and chamber size. Different upgrading scenarios were simulated under the same assumed condition as in the last section.

4.3.1 Better insulation

The studied climate chamber uses mineral fiber matting as insulation of the envelope. The thermal conductivity is 0.037 W/mK. Assume this fiber matting is substituted with another insulation material that has twice thermal resistance while it has the same thermal capacitance. The overall thermal resistance will be twice as high. The thermal capacitance is the same. By setting the overall thermal resistance as twice the original value and running the simulation under the same condition as mentioned in last chapter, the time needed to reach the target temperature is 60 min. The detailed parameters and results are listed in Table 2. Comparing with the original chamber, this time is about 1/3 shorter. When the thermal conductivity of the insulation decreases to ¼ value, the time is 47 minutes.

Table 2. Increasing the insulation of the climate chamber.

Insulation	Original	λx½	λx¼
Rtot [mK/W]	13.1	26.2	52.4
Heat loss [W/K]	76.3	38.2	19.1
Time constant [hour]	11.5	22.6	48.7
Time to reach 24.5 ^{o}C [hour]	1.5	1.0	0.8

4.3.2 Increase thickness

Usually the practical way to improve the chamber insulation is to increase the thickness of the insulation layer. This will lead to the increase of both thermal resistance and capacitance of the envelope. The incremental thermal resistance will increase the rate of the temperature rise while the increasing thermal capacity will have the opposite effect. Therefore it is a tradeoff when increasing the thermal insulation and inertia. When the envelope doubles its thickness, with the same testing condition it needs 63 minutes to reach the target temperature; when the thickness is increased to 4 times of the present value, the time is 48 minutes to reach 24.5 ^{o}C. Table 3 shows the result of the simulation.

Table 3. Increasing the thickness of the climate chamber.

Thickness	Original	dx2	dx4
Rtot [mK/W]	13.1	26.2	52.4
Cwall [kJ/K]	330	660	1320
Heat loss [W/K]	76.3	38.2	19.1
Time constant [hour]	11.5	33.3	48.7
Time to reach 24.5C [hour]	1.5	1.1	0.8

4.3.3 Change size

The chamber size and shape are vital factors for climate chambers. Smaller size means less air volume and less heat loss area, usually with better temperature mixture. On the other hand the chamber should have enough space for all the testing equipment as well as proper installing and operating space. Also it should not influence the air movement during the testing.

The present chamber is oversized for normal heat pump testing. If the chamber is constructed as half the size, the air volume will be half of he original one and the thermal resistance and capacitance will change too. When the chamber is cut into half size the envelope surface area decreases from 171 m^2 to 107 m^2. The resistance will increase due to the smaller exposed surface area. The thermal capacitance will decrease proportional to the area change. With these parameters the simulation gave the result that it takes 34 minutes to reach the target temperature. Another scenario is shrinking the chamber to ¼ of its original size and then the chamber surface area is decreased to 65 m^2. The time needed to reach target temperature is 14 minutes. After that a scenario with ¼ chamber size and double thickness of insulation layer is studied. The simulation result shows that the time to reach target temperature is 11 minutes. Table 4 lists the results and parameters for these scenarios.

Decreasing the size of the chamber has significant influence on the testing quality since this will decrease the heat loss and thermal inertial simultaneously.

Table 4. Changing the size of the climate chamber.

Size	Original	½ size	¼ size	¼ size& dx2
Surface Area [m^2]	171	107	65	65
Rtot [mK/W]	13.1	20.1	32	54.1
Cair [kJ/K]	90	45	23	23
Cwall [kJ/K]	330	193	112	224
Heat loss [W/K]	229	150	94	55
time constant[hour]	11.5	10.7	10.1	31.5
reach 24.5C [hour]	1.5	0.6	0.23	0.18

5 Conclusion

This chapter presents the conclusions from the chamber model investigation performed in this project. The questions listed in Aim and Scope chapter (1.2) will be answered here. Model application and chamber upgrading suggestions are concluded and future potentials of the project are stated.

5.1 Estimated thermal properties of the climate chamber

The overall heat loss factor of this chamber is 76.3 W/K, with the uncertainty of 0.24 W/K. The thermal conductivity and capacitance are listed in Table 5. The heat loss is higher than other chambers in the same laboratory, mainly due to the poor insulation and large surface area.

Table 5. Climate chamber thermal properties.

Thermal Properties of the Climate Chamber					
	Rtot	Ctot	Cair	Time constant	Heat Loss
Dimension	10^{-3} K /W	kJ/K	kJ/K	hour	W/K
Value	13.1	331	111	11.5	76.3±0.4

5.2 Model validation

The model can perform a simulation of the dynamic thermal process of the climate chamber. With the net power input to the chamber and ambient temperature as input data, the model gives the transient chamber inside temperature. The results matched the measurements well. The developed Matlab GUI programme gives an intuitive and easy way to adjust the model input and parameters. With the proper test data file, the programme can simulate the heat process and save the result automatically. The uncertainty of the measurement is 0.094 ^{o}C. The standard deviation between the model simulation and the measurement is 0.16 ^{o}C.

5.3 Simulations and test results

The comparison between the simulation and the Calorimeter method of heat pump testing was carried out to evaluate the quality of the testing. For the long term testing, when the initial and final thermal condition are the same and testing with stable heat pump working conditions, the simulation and the Calorimeter method give very close COP values.

While the testing includes large power variation such as defrosting cycles, there is some mismatch between these two methods. For the cases investigated in this project that include defrosting cycles, the COP values are 0.05-0.1 higher from the Calorimeter method than from the simulation results. This is because the heat balance is not well kept during testing and the Calorimeter method cannot deal with the heat storage effect.

The results tell that the Calorimeter method is valid and accurate for the testing with a steady condition. The weakness of this method is the lower accuracy for the short period dynamic process.

5.4 Defrosting process

Figure 24 is the heating capacities plot during heat pump defrosting process. The simulated result provides a better view of the heat capacity, especially the short-term changes. During defrosting period, the heating capacity goes down immediately when defrosting starts and then gradually recovers to working load after defrosting completes. The heating capacity from the simulation coincides with the working principle of the heat pump and gives a more accurate COP value.

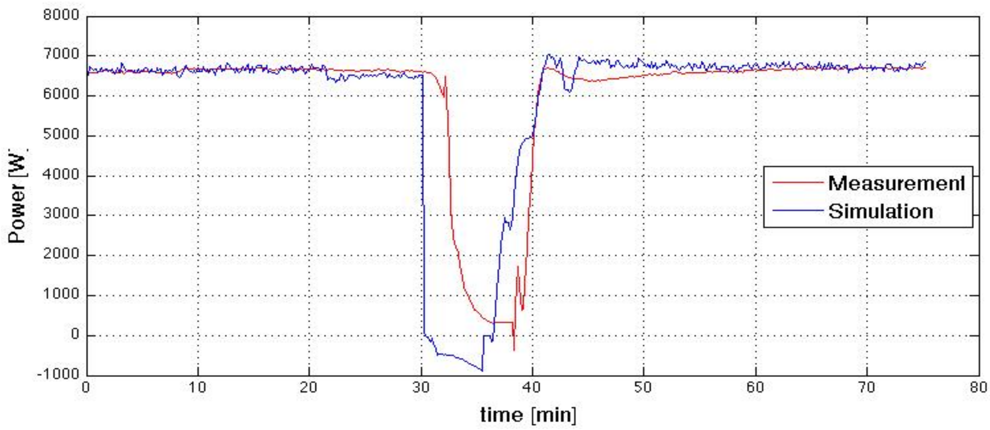


Figure 24. Heating capacity during defrosting; the simulation gave a better heating capacity profile.

5.5 Chamber upgrade

The thermal property of the chamber itself will influence the testing quality. According to the simulation results from different scenarios, the most significant factor to upgrade the climate chamber is the chamber size. By shrinking the size to 1/4, the time needed to reach target temperature in a certain condition shortens from 91 minutes to 14 minutes. This is because both the thermal inertia and the heat loss surface area decrease when the chamber gets smaller. Another way to improve the chamber is to increase the thickness of the insulation layer. The responding time decreases by 30 % when the thickness of the insulation is doubled.

The size of the chamber should be kept small besides the necessary equipment and operation space. A proper thickness of the envelope should also be chosen to improve the thermal insulation.

5.6 Future potential

The last part of the report states the potential for future development and application of the chamber model.

5.6.1 Use temperature to get power

The model can solve the condition only with power as input and temperature as output. To simulate a testing case, a first estimation of the heating capacity is needed. By developing of the model algorithm it is possible to use the measured chamber temperature as input and get the heating capacity of the heat pump directly.

5.6.2 Combine with control system

For heat pump testing with a climate chamber, the control system has a lag since it operates based on the sensor signal. The model simulation result can tell how and when the temperature will change, and by predicting the thermal process within the climate chamber the control system will have an immediate response. This can improve the testing quality of the climate chamber.

5.6.3 Expand the model

The investigation performed in this project only concerned one climate chamber. The model is capable to describe other similar chambers. The parameters can be obtained with the same method mentioned in Chapter 3 for any chambers. The model can also be used for simulations of real buildings. The real building heat flow simulation can help with building energy diagnoses and heating and cooling load evaluation.

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