Institutionen för systemteknik
Department of Electrical Engineering

Examensarbete

Model Based Diagnosis of an Air Source Heat Pump

Examensarbete utfört i Fordonssystem
vid Tekniska högskolan vid Linköpings universitet
av

Sandra Alfredsson

LiTH-ISY-EX--11/4502--SE

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Modellbaserad Diagnos av en Luftvärmepump
Model Based Diagnosis of an Air Source Heat Pump

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Sammanfattning
Abstract

The purpose of a heat pump is to control the temperature of an enclosed space. This is done by using heat exchange with a heat source, for example water, air, or ground. In the air source heat pump that has been studied during this master thesis, a refrigerant exchanges heat with the outdoor air and with a water distribution system.

The heat pump is controlled through the circuit containing the refrigerant and it is therefore crucial that this circuit is functional. To ensure this, a diagnosis system has been created, to be able to detect and isolate sensor errors. The diagnosis system is based on mathematical models of the refrigerant circuit with its main components: a compressor, an expansion valve, a plate heat exchanger, an air heat exchanger, and a four-way valve. Data has been collected from temperature- and pressure sensors on an air source heat pump. The data has then been divided into data for model estimation and data for model validation. The models are used to create test quantities, which in turn are used by a diagnosis algorithm to determine whether an error has occurred or not.

There are nine temperature sensors and two pressure sensors on the studied air source heat pump. Four fault modes have been investigated for each sensor: Stuck, Offset, Short circuit and Open circuit. The designed diagnosis system is able to detect all of the investigated error modes and isolate 40 out of 44 single errors. However, there is room for improvement by constructing more test quantities to detect errors and decouple more fault modes. To further develop the diagnosis system, the existing models can be improved and new models can be created.

Nyckelord
Keywords

modelling, diagnosis, vapour compression system

Abstract

The purpose of a heat pump is to control the temperature of an enclosed space. This is done by using heat exchange with a heat source, for example water, air, or ground. In the air source heat pump that has been studied during this master thesis, a refrigerant exchanges heat with the outdoor air and with a water distribution system.

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Sammanfattning

Syftet med en värmepump är att reglera temperaturen i ett avgränsat utrymme. Detta sker genom värmeutbyte med en värmekälla, till exempel vatten, luft eller mark. I den luftvärmepump som har studerats utbyter ett köldmedium värme med utomhusluft och med vatten i ett distributionssystem.

Luftvärmepumpen styrs genom kretsen som innehåller köldmediet och därför är det viktigt att denna fungerar. För att säkerställa detta har ett diagnossystem skapats för att kunna detektera och isolera sensorfel. Diagnossystemet är baserat på matematiska modeller av köldmediekretsen med dess huvudkomponenter: en kompressor, en expansionsventil, en plattvärmeväxlare, en luftvärmeväxlare och en fyrvägsventil. Data har samlats in från temperatur- och trycksensorer på en luftvärmepump. Datan har sedan delats upp i data för estimering och data för

validering av modeller. Modellerna används för att skapa teststorheter, som i sin tur används av en diagnosalgoritm för att avgöra om ett fel har uppstått eller ej.

På den studerade luftvärmepumpen finns nio temperatursensorer och två trycksensorer. För varje sensor har fyra olika felmoder undersökts: Fastnat, Offset, Kortslutning och Avbrott. Det framtagna diagnossystemet kan detektera alla undersökta fel och isolera 40 av 44 enkelfel. Emellertid finns det utrymme för förbättring genom att skapa fler teststorheter för att detektera fel och avkoppla fler felmoder. För att utveckla diagnossystemet ytterligare kan de befintliga modellerna förbättras och nya modeller kan skapas.

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Sandra Alfredsson
Arvika, September 2011

Contents

Chapter 1

Introduction

This chapter gives an introduction to the system for which the diagnosis system have been created. It describes the problem, the purpose, the goal and the expected results of the master thesis. A short review of related research is given and the chapter is ended with an outline of the remainder of the report.

1.1 Background

The purpose of a heat pump is to control the temperature of an enclosed space. This is done by using heat exchange with a heat source, for example water, air, or ground. A heat pump basically consists of a compressor, an expansion valve and two heat exchangers. There are also a number of sensors in a heat pump to monitor and control the heat exchange. There are four different heat sources from which the energy for the different types of heat pumps is collected: ground heat (vertical loop or horizontal loop), lake heat and air heat. An air source heat pump consists of two units: an indoor unit and an outdoor unit. The indoor unit consists of the control system and the water heater, while the actual heat pump is located in the outdoor unit. In the studied air source heat pump, the outdoor air exchanges heat with a refrigerant, which also exchanges heat with a water distribution system. The heat pump can be used for both heating and cooling. In this master thesis, the focus lies on model based diagnosis of the outdoor unit of an air source heat pump during heating production.

1.2 Problem formulation

The temperature sensors play an important role when it comes to the functionality of a heat pump. For example, due to air humidity, frost starts building on the air heat exchanger at low temperatures. When this happens, the air heat exchanger needs to be defrosted, but if there is an error in any of the temperature sensors, the defrost function may fail and the pump efficiency will be negatively affected.

When the heat pump is dysfunctional it would be very useful from a maintenance point of view to be able to narrow down the number of components that might be faulty, since it may be very time consuming to manually find the faulty component. Therefore it is desirable to detect and isolate errors in the sensors to minimise the risk of losing the functionality of the heat pump and to ease the maintenance of the pump.

1.3 Purpose and goal

The purpose of this master thesis is to find ways to diagnose possible sensor errors in an air source heat pump. The primary sensors to be considered are the temperature sensors in the refrigerant circuit. Other faults to be considered are broken pressure sensors. Errors to be investigated for all sensors are:

- Open circuit
- Short circuit
- Stuck
- Offset

The goal is to create models to be able to construct a model based diagnosis system. The components that should be modelled are: a compressor, a four-way valve, a plate heat exchanger, an expansion valve and an air heat exchanger. The components and their functionalities are described in Section 2.1. The diagnosis system should be active during heating production, but not during cooling production and defrosting. Since it is more likely that one error has occurred than several, the primary focus of the diagnosis system is to detect and isolate single faults.

1.4 Expected results

The master thesis should result in a number of models, from which test quantities should be created. The test quantities will be used by a diagnosis system to be able to detect and isolate sensor errors during stationary heating production.

1.5 Related research

There are two fundamental principles for constructing models: physical modelling and identification. Physical modelling means using knowledge of the system in order to create models, while identification means adapting the properties of the model to the properties of the system. For related work on this topic, see [4]. A heat pump basically consists of two heat exchangers, a compressor and an expansion valve. The properties of these components have been studied extensively and some of the relations can be found in for example [2] or [3]. Once models of a system are created, these can be used to create a diagnosis system by comparing the output of a model with the output of a sensor [6]. Since a diagnosis system that handles several behavioural modes in the sensors is desired, it is necessary to use an algorithm that can handle more than two modes per component. An algorithm of that kind has been developed in [5].

1.6 Outline of the master thesis

The outline of the master thesis is:

Chapter 1 gives an introduction to the system and why diagnosis is desired. The chapter also describes the purpose, the goals and the expected results of the master thesis.

Chapter 2 gives a description of the components and the functionality of the air source heat pump. It also provides a short description of the thermodynamics involved in a heat pump. Furthermore, the chapter contains the estimated models of the system and the fault models. The chapter is ended with an introduction to diagnosis.

Chapter 3 gives information regarding test conditions, how the data collection was carried out, which test points were used and how they were chosen.

Chapter 4 contains model validation and test quantity validation. The chapter also contains a detectability analysis and an isolability analysis.

Chapter 5 consists of the conclusions from tests and results and gives suggestions of improvements and future work.

Tables of abbreviations and nomenclature can be found in Appendix A.
The estimated parameters for the models are given in Appendix B.

Chapter 2

Theory

This chapter gives a description of how the studied heat pump is constructed and where the sensors are placed. Some thermodynamic concepts are introduced and the vapour-compression refrigeration cycle is described. Then the chosen models of the heat pump are stated and the chapter is ended with some diagnosis theory.

2.1 Heat pump construction

The main purpose of a heat pump is to maintain a high temperature in a heated space. This is done by absorbing heat from a source with low temperature and supplying this heat to the object of the heating. The studied heat pump can also be used to cool down a space. When cooling is the desired functionality, the heat pump absorbs heat from the space to be cooled and rejects it to the source used for absorbing heat during heating production. There is also a defrost mode, which is used when there is ice on the air exchanger.

The air source heat pump that has been studied during this master thesis consists of two units: an indoor unit and an outdoor unit. The actual heat pump is located in the outdoor unit, while the indoor unit consists of the control system and the water heater. A schematic view of the outdoor unit, also referred to as the refrigerant circuit, can be seen in Figure 2.1. The refrigerant circuit is connected to the distribution system indoors through (8) and (10). The compressor(1) is connected via the four-way valve(3) to the plate heat exchanger(6). The receiver(11) and the drying filter(13) are placed along the connection between the plate heat exchanger and the expansion valve(14). The expansion valve is connected to the air heat exchanger(16), which in turn is connected via the four-way valve to the compressor. There are nine temperature sensors, located at (2), (5), (7), (9), (12), (15), (17), (18), and (20). There are also two pressure sensors, located at (4) and (19). The heat pump components are described in the following sections.

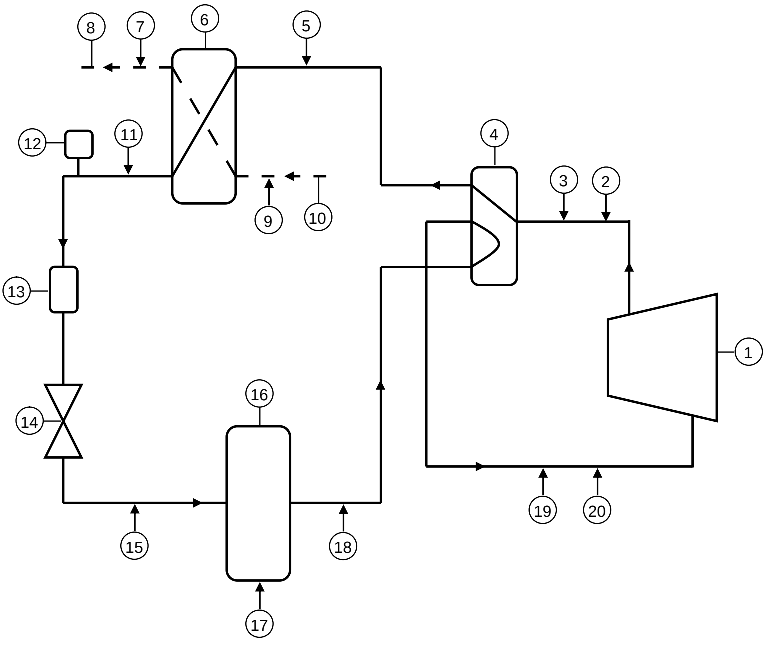

Figure 2.1. The refrigerant circuit at heating production. The picture shows the components, the sensors and the flow direction of the refrigerant and the water during heating production. A description of the components is given below.

Position	Description
1	Compressor
2	Temperature sensor (discharge pipe)
3	Pressure sensor (discharge pipe)
4	Four-way valve
5	Temperature sensor (ref 4)
6	Plate heat exchanger (condenser)
7	Temperature sensor (cond out)
8	Heating system (hot supply line)
9	Temperature sensor (cond in)
10	Heating system (cold return line)
11	Temperature sensor (ref 3)
12	Receiver
13	Drying filter
14	Electronic expansion valve
15	Temperature sensor (ref 2)
16	Air heat exchanger (evaporator)
17	Temperature sensor (defrost)
18	Temperature sensor (ref 1)
19	Pressure sensor (suction line)
20	Temperature sensor (suction line)

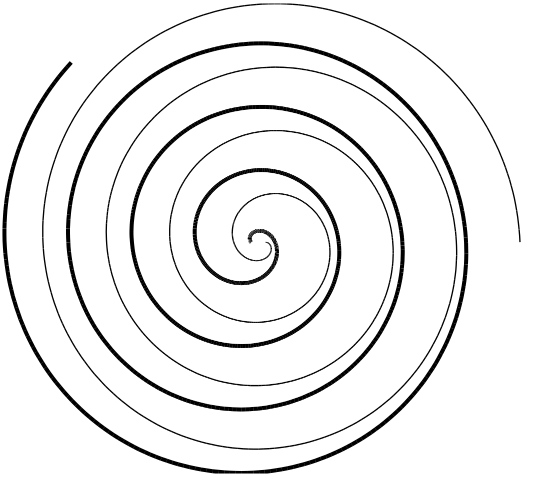

Figure 2.2. Illustration of scrolls in a scroll compressor.

2.1.1 Compressor

A compressor is a device that is used to increase the pressure and temperature of a fluid by reducing its volume. The compressor used in the test object is a scroll compressor and requires a power input. A scroll compressor consists of two spiral-shaped blades interleaved with each other, see Figure 2.2. Usually, one of the scrolls is fixed, while the other one moves in an orbit around a centre point without rotating. This traps the fluid between the scrolls, which compresses the fluid as the scroll moves.

2.1.2 Expansion valve

An expansion valve is a device that controls the mass flow of a fluid. In a heat pump, the expansion valve is used to control the mass flow of the refrigerant into the evaporator and thereby also the superheat and the subcooling (see Sections 2.2.3 and 2.2.4) of the refrigerant flowing out of the evaporator. The expansion valve in the test object is an electronic valve with a controllable input signal.

2.1.3 Heat exchangers

A heat exchanger is a construction where two mediums exchange heat. The heat exchange usually occurs through a wall that separates the mediums. The heat exchange is intended for the two fluids within the device, so the heat exchangers are usually well insulated. The fluids can be flowing in the opposite direction (counter flow), in the same direction (parallel flow), or perpendicular to each other (cross flow), see Figure 2.3.

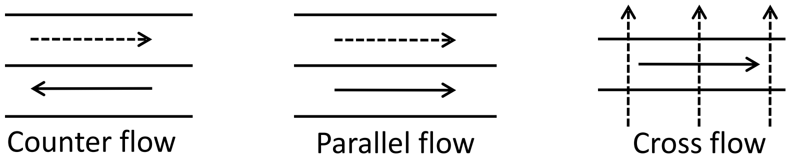

Figure 2.3. Schematics of different heat exchangers

Two types of heat exchangers are used in the test object: a plate heat exchanger and an air heat exchanger. These are described in the following sections.

Plate heat exchanger

The plate heat exchanger consists of several plates where the fluid passes through corrugated passages. The plates are usually made of metal or another material with high thermal conductivity. The plates give a large surface for the heat exchange, since the fluids are distributed over the plates. The two fluids flow through alternating passages, which means that the colder fluid always has two adjacent passages with warmer fluid. In the test object, the fluids flow in opposite directions (counter flow) during heating production.

Air heat exchanger

In the air heat exchanger, the refrigerant is distributed into different sections, flowing in pipes in both the perpendicular direction and in the opposite direction of the air flow. This makes the air heat exchanger a combination of a cross flow and a counter flow heat exchanger. The air is sucked through the air heat exchanger by a fan with a controllable input signal.

2.1.4 Four-way valve

The four-way valve is a device that makes it possible to control which way the fluid flows. In a heat pump, the four-way valve makes it possible to switch between running modes (heating, cooling or defrost). The four-way valve is constructed in a way that makes two flows of different temperature interact thermally with each other (this is however not the purpose of the valve, but needs to be considered in the modelling). Figures 2.4 and 2.5 illustrate the different settings of the valve. The section with dashed lines can be moved to change the flow path.

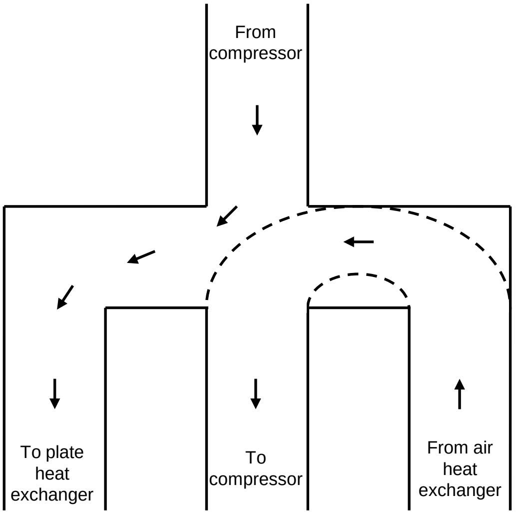

Figure 2.4. Schematic view of the refrigerant flow through a four-way valve at heating production.

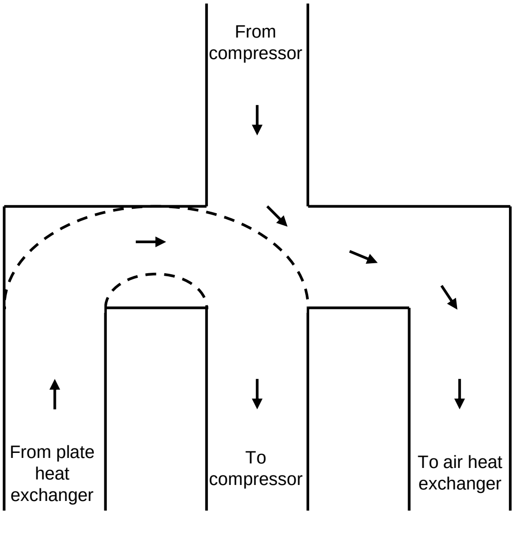

Figure 2.5. Schematic view of the refrigerant flow through a four-way valve at cooling production and defrost.

2.1.5 Receiver

The receiver is a small buffer tank, which stores excess refrigerant during heating production. The receiver is positioned at a pipe where the pressure is high during heating production, which means that the refrigerant is pushed into the receiver in this running mode. During cooling production and defrost, the pressure in the pipe is low, which makes the refrigerant leave the receiver.

2.1.6 Drying filter

The drying filter removes any water that may have been introduced in the refrigerant circuit, for example during filling of refrigerant. The water may otherwise freeze and clog up the circuit or reduce the performance of the pump due to the fact that the properties of water differ from the properties of the refrigerant.

2.2 Thermodynamics of a heat pump

A heat pump works in cycles, where a fluid (a substance in gas or liquid phase) called a refrigerant passes through four main components: a compressor, an expansion valve and two heat exchangers (a condenser and an evaporator). At the end of a cycle, the fluid returns to its initial state. The following sections describe the thermodynamics involved in a heat pump.

2.2.1 Ideal gas

An *ideal gas* is a theoretical gas where the only interactions between the particles are elastic collisions. An ideal gas follows the *ideal gas law*:

$$pV = mRT \tag{2.1}$$

where p is the pressure, V is the volume, m is the mass, R is the specific gas constant and T is the temperature. At standard temperature and pressure conditions, many gases behave approximately like an ideal gas.

2.2.2 Isentropic process

Ideal compression and ideal expansion take place at constant entropy. Such a process is called an *isentropic process*. For an ideal gas, the following holds:

$$pV^{\gamma} = C \tag{2.2}$$

where p is the pressure, V is the volume, γ is the heat capacity ratio, and C is a constant. The heat capacity ratio is defined as $\gamma = \frac{c_p}{c_v}$, where c_p and c_v are the specific heat capacities of the fluid at constant pressure and constant volume respectively. By using the ideal gas law, the following equation is obtained:

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} \tag{2.3}$$

where index 1 indicates before the compression/expansion and 2 indicates after.

2.2.3 Superheated vapour

At a given pressure, a pure liquid boils at a certain temperature. When boiling, the liquid changes phase into vapour and the temperature remains constant until all liquid has turned into vapour. If the heating continues when all liquid is vaporised, the temperature of the vapour starts rising. The difference between the temperature of the vapour and the temperature at which the liquid boils at the given pressure is called *superheat*, see the path between 1a and 1b in Figure 2.6. The superheat is used in a heat pump to ensure that no liquid enters the compressor, since that would eventually destroy the compressor.

2.2.4 Subcooled liquid

If the temperature of a liquid is lower than the saturation temperature at a given pressure, the liquid is *subcooled*, see the path between 3a and 3b in Figure 2.6. The subcooling of the refrigerant in a heat pump is done to ensure that no vapour enters the expansion valve, since that would affect the efficiency of the expansion valve in a negative way.

2.2.5 Temperature glide

When a refrigerant is composed of a mixture of components, it has no distinct boiling point. This is due to the fact that the different components of the mixture boil at different temperatures. In the condenser and the evaporator, the refrigerant is in both liquid and vapour phase. At a given pressure or temperature, the liquid and vapour phases contain different concentrations of the mixture components. This causes the boiling/condensing temperature for the liquid/vapour to vary. The total change in boiling/condensing point from one side of the heat exchanger to the other is called the *temperature glide*.

2.2.6 The vapour-compression refrigeration cycle

The most common cycle used for heat pump systems is the vapour-compression refrigeration cycle [2]. This cycle is shown in Figure 2.6. In the compressor, the vaporised refrigerant is compressed and the temperature and pressure rises (1 to 2). As the refrigerant passes through the condenser it rejects heat and condenses under constant pressure (2 to 3). The refrigerant then continues to the expansion valve where the pressure and temperature drops (3 to 4). In the evaporator, the refrigerant absorbs heat and evaporates under constant pressure (4 to 1). The cycle is completed as the refrigerant continues from the evaporator back to the compressor. In reality, the cycle differs from the ideal cycle. To make sure that only vapour, and no liquid, enters the compressor, the refrigerant is superheated (1a to 1b). Before the refrigerant enters the expansion valve, it is subcooled (3a to 3b), to ensure that there is no vapour in the refrigerant.

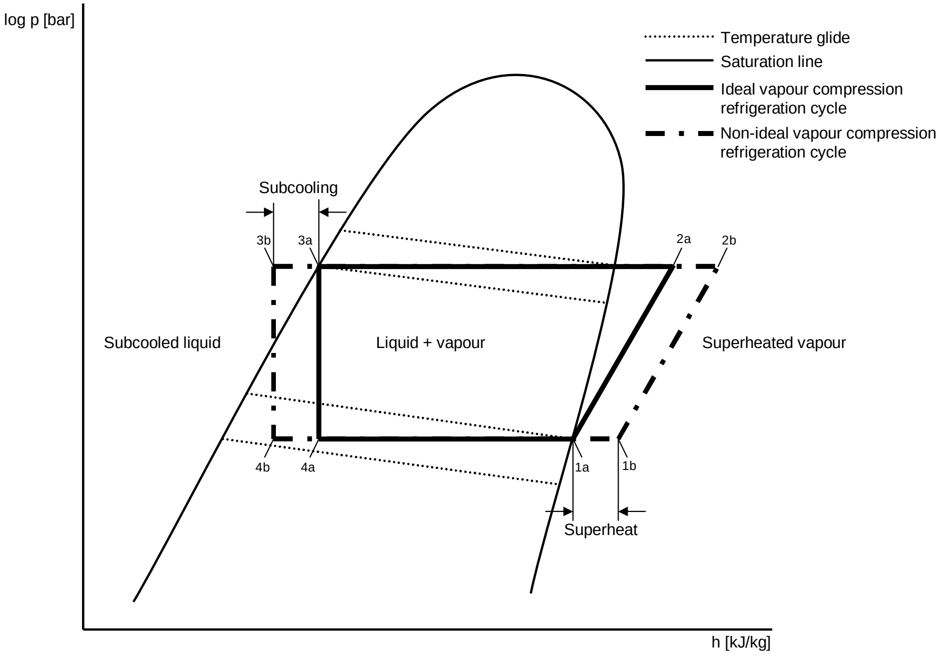

Figure 2.6. The vapour compression refrigeration cycle. The solid bold line marks the ideal vapour-compression refrigeration cycle and the bold dash dotted line shows the non-ideal cycle.

2.3 Heat pump models

The diagnosis system is based on mathematical models of the heat pump. Models for the compressor, four-way valve, plate heat exchanger, expansion valve and air heat exchanger have been developed. These models are presented in the following sections. The placement of the sensors measuring the temperatures and pressures can be found in Figure 2.1.

2.3.1 Compressor

The compressor is modelled by a first order low pass filter applied to the compressor model in [1]:

$$\tau_{disch}\dot{T}_{disch} + T_{disch} = T_{suct}\left(1 + \frac{\Pi^{\frac{\gamma-1}{\gamma}} - 1}{\eta_{comp}}\right) \tag{2.4}$$

where τ is a time constant, $\Pi = \frac{p_{disch}}{p_{suct}}$, γ is the specific heat capacity ratio for the refrigerant and η_{comp} is the compressor efficiency. Some similarities to (2.3) can be seen in the model, for example dependency of pressure ratio and heat capacity ratio. The differences are due to that in reality, the compression is not ideal.

To calculate the model output, the estimation of the derivative is used in Euler's method:

$$y(t + T_s) = y(t) + T_s\dot{y}(t) \tag{2.5}$$

where T_s is the sample time. The complete model is given by (2.6).

$$T_{disch}(t + T_s) = T_{disch}(t) + \frac{T_s}{\tau_{disch}}\left(T_{suct}(t)\left(1 + \frac{\Pi(t)^{\frac{\gamma-1}{\gamma}} - 1}{\eta_{comp}}\right) - T_{disch}(t)\right) \tag{2.6}$$

2.3.2 Expansion valve

The expansion valve is modelled in the same way as a turbine is modelled in [1]:

$$T_{ref2} = T_{ref3}\left(1 - \left(1 - \Pi^{-\frac{\gamma-1}{\gamma}}\right)\eta_{exp}\right) \tag{2.7}$$

where $\Pi = \frac{p_{suct}}{p_{disch}}$, γ is the specific heat capacity ratio for the refrigerant and η_{exp} is the expansion valve efficiency.

2.3.3 Heat exchangers

The efficiency of a heat exchanger is measured through its temperature transfer efficiency, η. The definition of η for a fluid i is given in [7]:

$$\eta_i = \frac{\Delta_i}{\Theta}, \tag{2.8}$$

where Δ_i is the temperature difference for fluid i before and after the heat exchanger and Θ is the difference between the temperatures of the two fluids before

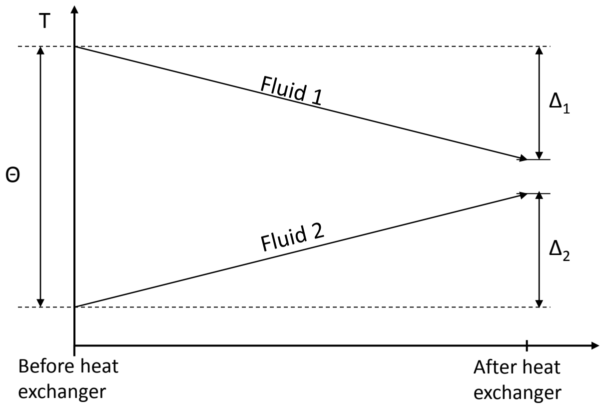

Figure 2.7. Definitions of Θ, Δ_1 and Δ_2

the heat exchanger, see Figure 2.7. The temperature transfer efficiency can assume values between 0 and 1. A value of 1 would mean that the colder fluid would assume the temperature of the hotter fluid, which is physically impossible, since there is always heat losses in a real system.

Plate heat exchanger

The plate heat exchanger was modelled in accordance with (2.8). For the refrigerant circuit, Δ and Θ are given by $\Delta = T_{ref4} - T_{ref3}$ and $\Theta = T_{ref4} - T_{cond\_in}$, which gives the model:

$$T_{ref3} = T_{ref4} - \eta_{phe\_ref}(T_{ref4} - T_{cond\_in}) \tag{2.9}$$

For the water distribution system, Δ and Θ are given by $\Delta = T_{cond\_out} - T_{cond\_in}$ and $\Theta = T_{ref4} - T_{cond\_in}$. The model output is calculated as:

$$T_{cond\_out} = T_{cond\_in} + \eta_{phe\_water}(T_{ref4} - T_{cond\_in}) \tag{2.10}$$

Air heat exchanger

The air heat exchanger has been modelled with temperature transfer efficiency in the same way as the plate heat exchanger. With $\Delta = T_{ref1} - T_{ref2}$ and $\Theta = T_{ref2} - T_{defrost}$, the model is given by:

$$T_{ref1} = T_{ref2} + \eta_{ahe}(T_{ref2} - T_{defrost}) \tag{2.11}$$

2.3.4 Four-way valve

The four-way valve resembles a heat exchanger and is therefore modelled with temperature transfer efficiency in accordance with (2.8). By studying Figure 2.4, the conclusion is that the four-way valve resembles a parallel flow heat exchanger at heating production.

The model for the part of the four-way valve connecting the air heat exchanger and the compressor at heating production is given by the following equation:

$$T_{suct} = T_{ref1} + \eta_{4wv\_suct}(T_{disch} - T_{ref1}) \tag{2.12}$$

where η_{4wv_suct} is the temperature transfer efficiency.

The part of the four-way valve connecting the compressor and the plate heat exchanger at heating production is modelled by:

$$T_{ref4} = T_{disch} + \eta_{4wv\_disch}(T_{disch} - T_{ref1}) \tag{2.13}$$

where η_{4wv_disch} is the temperature transfer efficiency.

2.4 Sensor fault models

To be able to evaluate the diagnosis system when a fault has occurred, the different fault modes need to be modelled. These models are stated in Table 2.1.

Sensor fault mode	**Sensor output**
Stuck (Temperature sensor)	$T_{output} = T_s$, where T_s is a constant
Offset (Temperature sensor)	$T_{output} = T + k$, where T is the true value and k is a constant
Open circuit (Temperature sensor)	$T_{output} > k_{oc,T}$, where $k_{oc,T}$ is a positive constant
Short circuit (Temperature sensor)	$T_{output} < k_{sc,T}$, where $k_{sc,T}$ is a negative constant
Stuck (Pressure sensor)	$p_{output} = p_s$, where p_s is a constant
Offset (Pressure sensor)	$p_{output} = p + k$, where p is the true value and k is a constant
Open circuit (Pressure sensor)	$p_{output} < k_{oc,p}$, where $k_{oc,p}$ is a negative constant
Short circuit (Pressure sensor)	$p_{output} > k_{sc,p}$, where $k_{sc,p}$ is a positive constant

Table 2.1. Fault models

2.5 Diagnosis

The purpose of diagnosis is to detect and isolate errors in a system. Ideally, a diagnosis system should be able to detect and isolate all errors occurring in a system.

When a detectable error occurs, there is a difference between what is observed and how the system should behave in the fault-free case. The diagnosis system uses a diagnosis algorithm, which in turn uses test quantities, in order to determine whether or not an error has occurred. The diagnosis system then generates diagnoses, i.e., conclusions of the reason for the system behaviour.

In a diagnosis system there is always a risk of false alarm and missed alarm. A false alarm is when the diagnosis system produces fault diagnoses even though no error has occurred. A missed alarm is when an error has occurred, but the diagnosis system did not detect it. The diagnosis system is designed to make the likelihood of false alarm and missed alarm as small as possible.

2.5.1 Concepts

To be able to understand the diagnosis algorithm presented in Section 2.5.2, the following sections describe some of the concepts.

Sets and conflicts

The components of the system are represented by a *set* $\mathcal{C}$. The set $\mathcal{C}$ consists of component variables c_i and $\mathbf{R}_{c_i}$ is the *domain* of possible behavioural modes for component c_i. When the observations of the system are different from the behaviour of the system in fault free mode it results in a *conflict*. For a conflict, C, it holds that C$\subseteq \mathcal{C}$, i.e., not all components in C are fault free. A conflict C_1 is called a *minimal conflict* if there is no other conflict C_2 such that $C_2 \subset C_1$.

Semantic consequence

A formula, A, is a *semantic consequence* of another formula, B, if and only if the set of interpretations that make all members of B true is a subset of the set of interpretations that make A true [8]. This is written $A \models B$. The following examples give an illustration of a case when A is a semantic consequence of B and a case when A is not a semantic consequence of B.

Example 2.1: $A \models B$

Let
$A =$ sensor1 $\in$ {'Offset'}
and
$B =$ sensor1 $\in$ {'Stuck','Offset'} $\vee$ sensor2 $\in$ {'Open circuit'}

The interpretation of A is that sensor 1 has an offset. The interpretation of B is that sensor 1 is stuck or has an offset *or* sensor 2 is open circuit. In this case A is a semantic consequence of B, since the interpretation of A also is a valid interpretation of B.

Example 2.2: $A \not\models B$

Let
$A =$ sensor1 $\in$ {'Open circuit'}
and
$B =$ sensor1 $\in$ {'Stuck','Offset'} $\vee$ sensor2 $\in$ {'Open circuit'}

In this case, A is *not* a semantic consequence of B since there is no interpretation of B that says that sensor 1 is open circuit.

Maximal normal form

Let M ($M \in \mathbf{R}_{c_i}$) be the set of behavioural modes that c_i is in and let D_i denote a conjunction (a combination of *and*-statements) on the form

$$c_1 \in M_1 \wedge c_2 \in M_2 \wedge ... \wedge c_n \in M_n \tag{2.14}$$

where $c_i \not\equiv c_j$ if $i \neq j$. If a disjunction (a combination of *or*-statements) is formed from a set of such conjunctions, i.e., $D_1 \vee D_2 \vee ... \vee D_m$, it is said to be in *maximal normal form (MNF)* if

1. No conjunction is a consequence of another conjunction, i.e., it does not hold that $D_i \models D_j$ if $i \neq j$.
2. Each M_i is a non-empty proper subset of R_{c_i}, i.e., $\emptyset \neq M_i \subset R_{c_i}$.

Maximal normal form is described more extensively in [5].

Hitting set

Let $\mathbb{C}$ be the set of all minimal conflicts. If it holds for all conflicts $C \in \mathbb{C}$, that $\delta \cap C \neq \emptyset$, then δ is a diagnosis. In other words, δ is a diagnosis if it is a *hitting set* with respect to $\mathbb{C}$.

2.5.2 Generalised minimal hitting set algorithm

Since the sensors can behave in different ways, depending on what the fault is, a diagnosis algorithm that can handle several behavioural modes is needed. A diagnosis algorithm of that kind has been developed in [5] and is presented in this section. The generalised minimal hitting set algorithm computes an output that characterises all diagnoses. It takes into consideration that a component can have several behavioural modes and assumes that a component cannot be in several behavioural modes at the same time. When a conflict occurs, the diagnosis algorithm computes a diagnosis with all the behavioural modes of the negated conflict. If a new conflict occurs, the diagnosis algorithm investigates whether or not the new conflict can be explained by the current diagnosis. If that is not the case, the algorithm computes a new diagnosis that explains both conflicts.

The algorithm uses formulas in MNF, with the benefit that formulas in MNF do not contain redundant information. For the algorithm to be able to produce an output with possible diagnoses, it needs the negated conflicts as an input. The resulting diagnoses of the algorithm need to be able to explain why all the conflicts have occurred, and therefore the hitting sets are used. In other words, if a conflict has occurred, the resulting diagnose should contain information that describes why the conflict has occurred. The diagnosis algorithm can be expressed as follows:

input: a formula D in MNF and a negated conflict P
output: Q (diagnosis)

$D_{old} := D$
$D_{add} :=$ empty formula
$\forall\ D_i \in D$ **do**
if $D_i \not\models P$ **then**
Remove D_i from D_{old}
$\forall\ P_j \in P$ **do**
Let D_{new} be a conjunction in MNF such that $D_{new} \simeq D_i \wedge P_j$
$\forall\ D_k \in D, D_k \neq D_i$ **do**
if $D_{new} \models D_k$ **then goto** LABEL1
end
$D_{add} := D_{add} \vee D_{new}$
LABEL1
end
end
end
$Q := D_{old} \vee D_{add}$

2.5.3 Test quantities

A test quantity is a relation that indicates when something is wrong with the system. A test quantity, T, can for example be constructed as the difference between a model that estimates a certain quantity and a sensor that measures the same quantity. This is called a residual. For example, a resistor can be modelled by Ohm's law, $u = Ri$, where u is the voltage, R is the resistance and i is the current. If $\hat{u}$ is the output of the model and u is the output of a sensor measuring the voltage, a possible test quantity could be $T = \hat{u} - u$. In the fault free case, ideally T should equal zero. However, no models are perfect, so there will always be a small difference between the measured value and the estimated value. Therefore, the test quantity is compared with a threshold, J. If T>J it is an indication that something is wrong with the system.

A test quantity is sensitive to a set of component faults in the system. When a test quantity exceeds its threshold, a conflict occurs. The conflict says that all the components in the set cannot be fault free.

More extensive information about model based diagnosis can be found in [6].

Chapter 3

Experiment set-up

This chapter describes how the data collection was carried out, which test points were used and how they were chosen.

3.1 Measurements

The measurements took place in a climate chamber where the air source heat pump was run at ambient temperatures between -20 °C and 12 °C. The moist level of the air was also varied, but this data was not registered. The desired temperature of the water in the supply line varied between 35 °C and 60 °C. A total of 19 test scenarios, stated in Table 3.1, were used. The sensor data was sampled at stationary conditions with a frequency of 0.1 Hz. The test points were chosen to represent a wide range of scenarios, but also due to required performance reports in the heat pump industry. The length of the datasets vary a lot, merely due convenience during data collection (data sufficient for performance report, data collected overnight, et cetera).

At the start-up of a heat pump, it takes a while (about 5 to 10 minutes) before the system is stabilised. The main reasons for that is that the expansion valve needs some time to adjust the superheat, the air flow through the fan is not stable at first, and the fluid in the distribution system needs some time to circulate. No data was collected until the system was stabilised.

Sensor reactions at short circuit and open circuit were investigated and faults in accordance with the fault models in Table 2.1 were injected in some fault free data sets, to be able to verify the functionality of the diagnosis algorithm.

Table 3.1. Test scenarios of an air source heat pump

T_{amb} [°C]	T_{cond_out} [°C]	Length of dataset(s) [hh:mm:ss]
12	35	00:53:20
12	50	14:24:10, 00:42:30
7	35	17:58:30
7	45	03:14:20
7	50	03:08:50
7	55	18:34:20[1]
7	60	04:15:20[1]
2	35	05:22:10
2	45	18:04:50[1], 23:21:50
2	55	04:03:10[1]
-7	35	15:30:20, 02:09:20
-7	45	03:29:50[1]
-7	50	16:10:50
-7	55	03:27:00[1]
-15	35	18:22:50
-15	50	02:57:50
-20	35	45:54:00[1]
-20	50	17:37:50[1]

[1] The sensor measuring T_{ref2} had loosened from the pipe and ice was building between the pipe and the sensor during data collection.

Chapter 4

Results

This chapter contains validations for the models stated in Section 2.3. It also gives a description of how the test quantities were created and illustrates how some test quantities behave when there is a fault present in the system. The chapter is ended with a detectability analysis and an isolability analysis.

4.1 Model validation

In the following sections, the model validations are presented. The model validation has been done with data that has not been used in the model estimation, to make sure that the models are not adapted to the specific disturbance signals in the estimation data.

The parameters for the models were calculated from measurement data and then estimated as functions or constants. When data from the same test point rendered different calculations of a parameter, a mean value of these was calculated.

The data from the sensors measuring T_{ref1} and T_{suct}has been low pass filtered. The estimated time constants, τ_{ref1} and τ_{suct}, for the low pass filters are given in Appendix B. The filtering was done because these temperatures were very sensitive to fluctuations in ambient temperature and humidity.

The estimated parameters, a_1, a_0 and C, for the models and the time constant, τ_{disch}, for the compressor model are given in Appendix B. The specific heat capacity ratio of the refrigerant is $\gamma = 1.21$.

4.1.1 Compressor

The compressor efficiency was approximated with a linear function of the pressure ratio:

$$\eta_{comp} = \eta_{comp}(\Pi) = a_{1,comp}\frac{p_{disch}}{p_{suct}} + a_{0,comp}$$

Figure 4.1 shows a validation of the compressor model. For all data that has been collected, the model gives a deviation of at most 15.1 °C. The deviation is largest

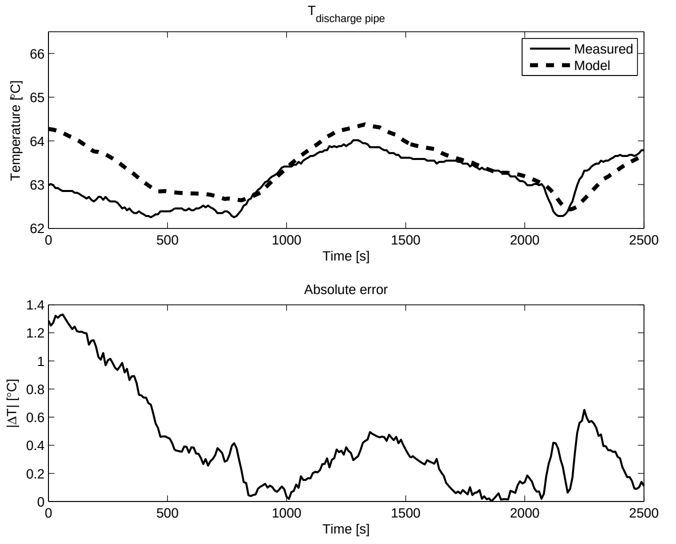

Figure 4.1. Validation of the compressor model. This is an extraction from the data set $T_{amb} = 7°\text{C}$ and $T_{cond\_out} = 35°\text{C}$. In the top plot, the measured data from T_{disch} and the output from the compressor model are plotted. The absolute difference between those two curves is plotted in the bottom plot.

at low ambient temperatures, which may be caused by how the components of the heat pump are affected by low temperatures.

The compressor model gives a rather large deviation from measured values. The reason for that might be that the mass flow has not been considered in the model. It seems reasonable to believe that the mass flow has some influence on the resulting temperature and pressure.

For the temperature sensor on the discharge pipe, a negative offset would be worse than a positive offset, due to the fact that the compressor needs to be turned off at temperatures above 140°C, otherwise the compressor might be damaged. This function relies on the temperature sensor on the discharge pipe and it might have been useful to make a difference between a positive offset and a negative offset, rather than just checking the absolute error.

4.1.2 Expansion valve

The expansion valve efficiency was approximated with a linear function of the pressure ratio:

$$\eta_{exp} = \eta_{exp}(\Pi) = a_{1,exp}\frac{p_{suct}}{p_{disch}} + a_{0,exp}$$

Figure 4.2 shows the result from the validation of the expansion valve model. The maximum absolute error of the model for the expansion valve is 3.9 °C.

Since the temperature measured between the expansion valve and the air heat exchanger is used to determine when to end a defrost, it is rather important to have

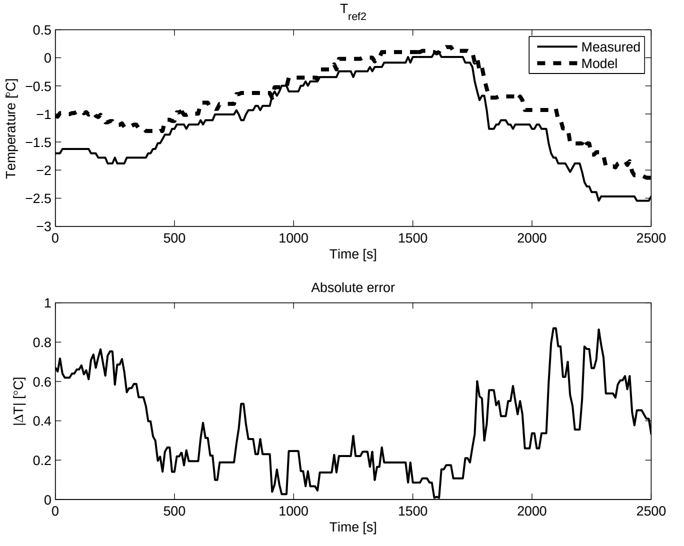

Figure 4.2. Validation of the expansion valve model. This is an extraction from the data set $T_{amb} = -7°C$ and $T_{cond\_out} = 50°C$. In the top plot, the measured data from T_{ref2} and the output from the expansion valve model are plotted. The absolute difference between those two curves is plotted in the bottom plot.

a good model. Just as for the compressor, the mass flow has not been considered in the model. The expansion valve has a variable opening degree, but without access to the actuator signal, there is no way of incorporating this into the model. For the test quantities based on the model for the expansion valve it might, just as for the compressor, be useful to check whether the offset is positive or negative, because a positive offset would mean that the defrost ends too early, when there is still ice left on the air heat exchanger. This would in turn affect the efficiency of the heat pump.

4.1.3 Plate heat exchanger

The temperature transfer efficiency for the refrigerant circuit was estimated as a constant:

$$\eta_{phe\_ref} = C_{phe\_ref}$$

For the distribution system the temperature transfer efficiency was estimated as a linear function of Θ:

$$\eta_{phe\_water} = \eta_{phe\_water}(\Theta) = a_{1,phe\_water}(T_{ref4} - T_{cond\_in}) + a_{0,phe\_water}$$

The validations for the plate heat exchanger models are shown in Figures 4.3 and 4.4. The maximum absolute error is 4.3 °C for the refrigerant circuit and 6.1 °C for the distribution system.

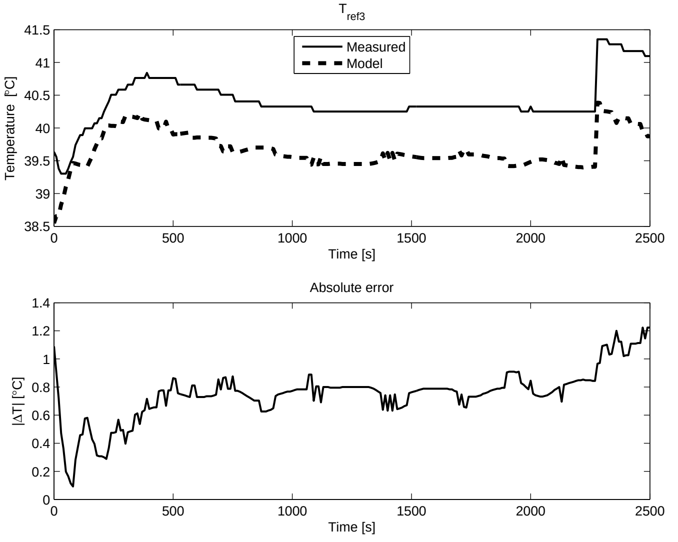

Figure 4.3. Validation of the plate heat exchanger model for the refrigerant circuit. This is an extraction from the data set $T_{amb} = -20°\text{C}$ and $T_{cond\_out} = 50°\text{C}$. In the top plot, the measured data from T_{ref3} and the output from the plate heat exchanger model are plotted. The absolute difference between those two curves is plotted in the bottom plot.

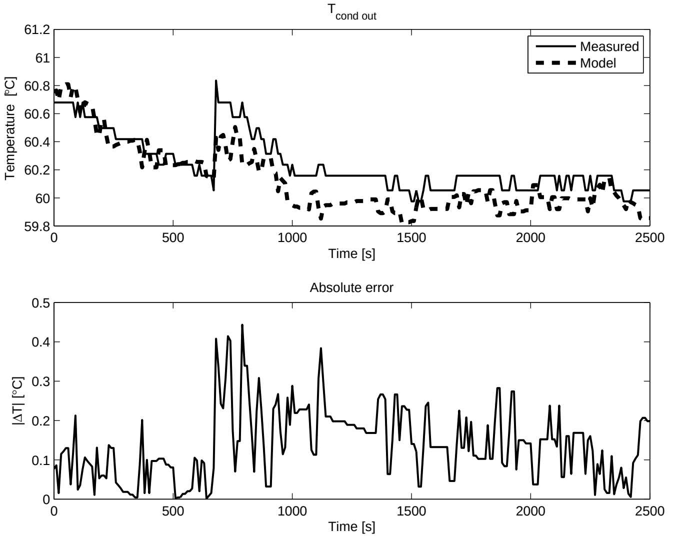

Figure 4.4. Validation of the plate heat exchanger model for the distribution system. This is an extraction from the data set $T_{amb} = 7°\text{C}$ and $T_{cond\_out} = 55°\text{C}$. In the top plot, the measured data from T_{cond_out} and the output from the plate heat exchanger model are plotted. The absolute difference between those two curves is plotted in the bottom plot.

The temperature transfer efficiency of the plate heat exchanger was estimated as a constant for the refrigeration circuit, which is a rather large approximation, but it seems to work satisfactory in this case. Unlike the output temperatures of the compressor and the expansion valve, the sign of the offset of the temperature sensor between the plate heat exchanger and the expansion valve does not have any significance for the control of the refrigerant circuit.

4.1.4 Air heat exchanger

The estimation of the temperature transfer efficiency for the air heat exchanger resulted in an inverse function of Θ:

$$\eta_{ahe} = \eta_{ahe}(\Theta) = \frac{C_{ahe}}{T_{ref2} - T_{defrost}}$$

This rendered a model of the air heat exchanger with a constant temperature drop from the temperature of the inlet refrigerant. A validation for the air heat exchanger is presented in Figure 4.5. For this model, the maximum absolute error is 5.2 °C.

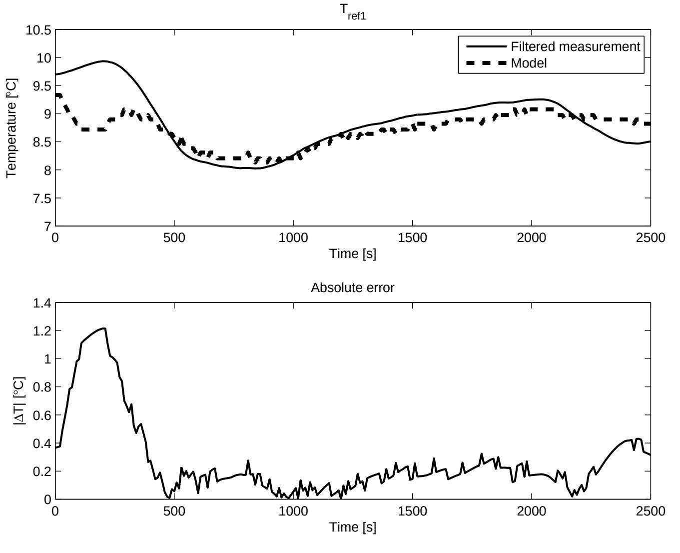

Figure 4.5. Validation of the air heat exchanger model. This is an extraction from the data set $T_{amb} = 12°\mathrm{C}$ and $T_{cond\_out} = 50°\mathrm{C}$. In the top plot, the filtered data from T_{ref1} and the output from the air heat exchanger model are plotted. The absolute difference between those two curves is plotted in the bottom plot.

The model for the air heat exchanger is a decrease of the inlet temperature by a constant. The reason for the decrease in temperature is the fact that the refrigerant changes phase from liquid to gas in the air heat exchanger, which requires energy. With mass flow models for the expansion valve and the compressor and the actuator signal for the fan, it would be possible to make a more sophisticated model of the air heat exchanger. It also seems reasonable to believe that the outdoor temperature could be used for further improvement of the model.

4.1.5 Four-way valve

The temperature transfer efficiencies, η_{4wv_suct} and η_{4wv_disch}, were both estimated as linear functions of Θ, which in both cases is $T_{disch} - T_{ref1}$. This gives:

$$\eta_{4wv\_suct} = \eta_{4wv\_suct}(\Theta) = a_{1,4wv\_suct}(T_{disch} - T_{ref1}) + a_{0,4wv\_suct}$$

and

$$\eta_{4wv\_disch} = \eta_{4wv\_disch}(\Theta) = a_{1,4wv\_disch}(T_{disch} - T_{ref1}) + a_{0,4wv\_disch}$$

The validation for the models of the four-way valve are shown in Figures 4.6 and 4.7. Figure 4.6 represents the part of the four-way valve that connects the air heat exchanger and the compressor during heating production and Figure 4.7 is a validation of the model for the section of the four-way valve that connects the compressor and the plate heat exchanger during heating production. The maximal absolute errors are 4.2 °C and 1.9 °C respectively.

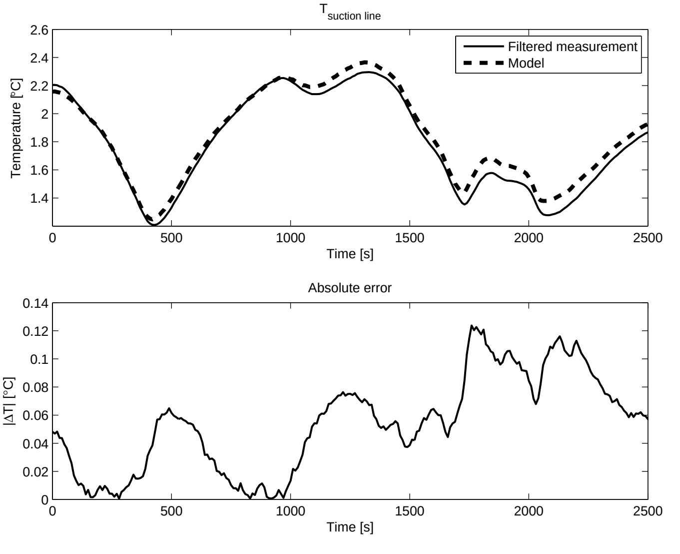

Figure 4.6. Validation of the four-way valve model of the connection between the air heat exchanger and the compressor. This is an extraction from the data set $T_{amb} = 2°C$ and $T_{cond\_out} = 45°C$. In the top plot, the filtered data from T_{suct} and the output from the four-way valve model are plotted. The absolute difference between those two curves is plotted in the bottom plot.

An alternative model of the part of the four-way valve connecting the air heat exchanger and the compressor was created in order to be able to estimate T_{suct}

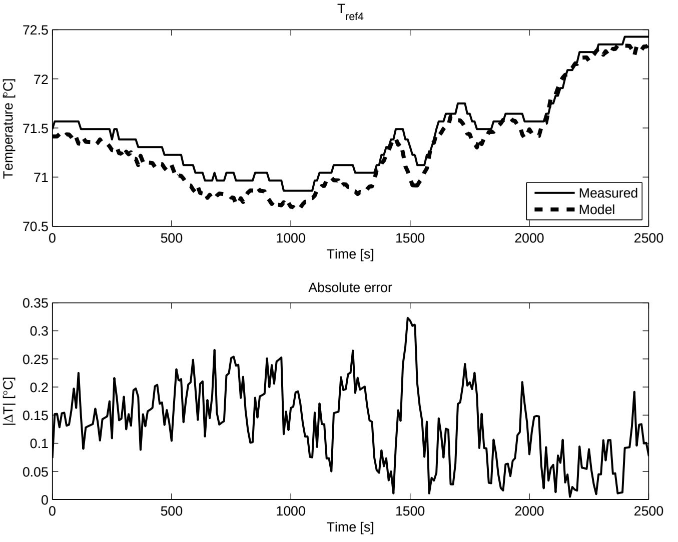

Figure 4.7. Validation of the four-way valve model of the connection between the compressor and the plate heat exchanger. This is an extraction from the data set $T_{amb} = -20°\mathrm{C}$ and $T_{cond\_out} = 35°\mathrm{C}$. In the top plot, the data from T_{ref4} and the output from the four-way valve model are plotted. The absolute difference between those two curves is plotted in the bottom plot.

without using T_{disch}. The reason for that is further explained in Section 4.2.2. In the alternative model, T_{disch} was neglected, which gave the model:

$$T_{suct\_alt} = T_{ref1} + \eta_{4wv\_suct\_alt} T_{ref1} \tag{4.1}$$

where $\eta_{4wv\_suct\_alt}$ was estimated as a linear function of T_{ref1}:

$$\eta_{4wv\_suct\_alt} = \eta_{4wv\_suct\_alt}(T_{ref1}) = a_{1,4wv\_suct\_alt} T_{ref1} + a_{0,4wv\_suct\_alt}$$

A validation of the alternative model can be seen in Figure 4.8.

The models for the four-way valve are not as accurate as one may think they would be, due to the simplicity of the construction of the valve. When comparing the models, the maximal absolute error differs quite a bit too. This could be due to additional heat losses from the pipes. A way to improve the models could be to model the heat losses in the pipes.

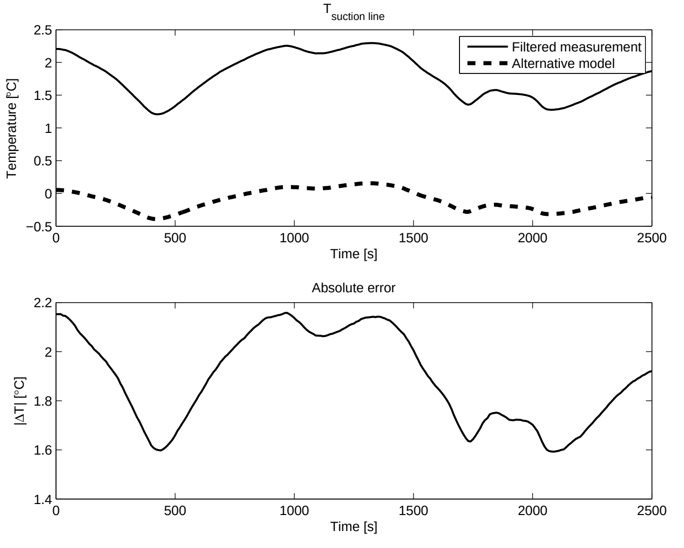

Figure 4.8. Validation of the alternative four-way valve model of the connection between the air heat exchanger and the compressor. This is an extraction from the data set $T_{amb} = 2°\text{C}$ and $T_{cond\_out} = 45°\text{C}$. In the top plot, the filtered data from T_{suct} and the output from the alternative four-way valve model are plotted. The absolute difference between those two curves is plotted in the bottom plot.

4.2 Test quantity validation

A total number of 26 test quantities have been created. The structures of these test quantities are described below. The thresholds for the residuals have been chosen as an increase of 10% of the maximal absolute error of the models.

4.2.1 Model based test quantities

The test quantities based on the models of the components are all constructed in a similar way. An example of such a test quantity is given by the difference between the output of the model of a four-way valve and the sensor measuring the same quantity:

$$\begin{aligned} T_1 &= \hat{T}_{suct} - T_{suct} \\ &= T_{ref1} + \eta_{4wv\_suct}(T_{disch} - T_{ref1}) - T_{suct} \end{aligned} \tag{4.2}$$

where T_1 is test quantity one, $\hat{T}_{suct}$ is the output of the model, T_{suct} is the output of the sensor. This test quantity is sensitive to the following faults:

$T_{ref1} \in \{$'Stuck','Offset','Open circuit','Short circuit'$\}$,
$T_{disch} \in \{$'Stuck','Offset','Open circuit','Short circuit'$\}$ and
$T_{suct} \in \{$'Stuck','Offset','Open circuit','Short circuit'$\}$.

Figure 4.9 illustrates this test quantity and the corresponding threshold.

Test quantities based on the other models were created analogously. Additionally, a test quantity comparing the difference between the temperatures T_{ref2} and $T_{defrost}$ was created in order to be able to detect offsets in the sensor measuring $T_{defrost}$.

4.2.2 Model based test quantities with estimated inputs

To increase the isolability, sensor outputs in the test quantities were replaced by model outputs of the preceding component. In test quantity one above, T_{ref1} is replaced by $\hat{T}_{ref1}$, which gives the following test quantity:

$$\begin{aligned} T_2 &= \hat{T}_{suct} - T_{suct} \\ &= \hat{T}_{ref1} + \hat{\eta}_{4wv\_suct}(T_{disch} - \hat{T}_{ref1}) - T_{suct} \\ &= T_{ref2} + C + \hat{\eta}_{4wv\_suct}(T_{disch} - (T_{ref2} + C)) - T_{suct} \end{aligned} \tag{4.3}$$

This test quantity is sensitive to the following faults:

$T_{ref2} \in \{$'Stuck','Offset','Open circuit','Short circuit'$\}$,
$T_{disch} \in \{$'Stuck','Offset','Open circuit','Short circuit'$\}$ and
$T_{suct} \in \{$'Stuck','Offset','Open circuit','Short circuit'$\}$.

This method was applied to all residuals created in accordance with Section 4.2.1 except the residuals based on the model of the section with the water distribution system in the plate heat exchanger and the model of the compressor.

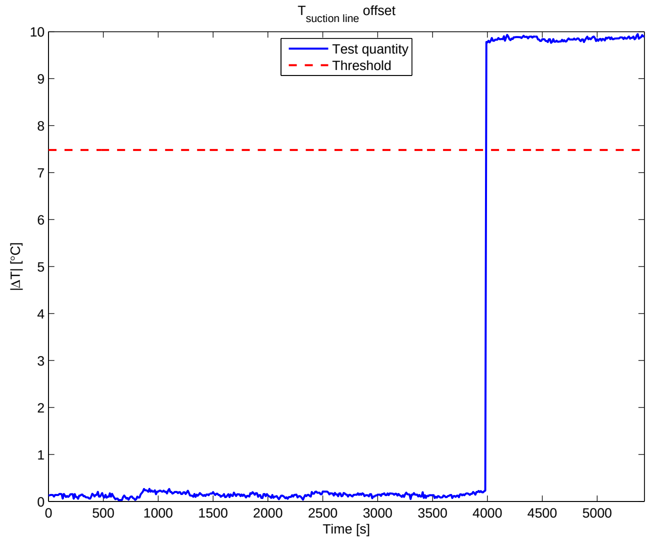

Figure 4.9. Test quantity based on the model of a four-way valve. At t=4000s an offset occurs in the sensor measuring T_{suct} and the test quantity exceeds its threshold.

For the model of the section with the water distribution system in the plate heat exchanger, the sensor output of T_{cond_in} cannot be replaced by a model output, since there is no model of the rest of the water distribution system, i.e., no model with $\hat{T}_{cond\_in}$ as output.

For the compressor model, T_{suct} cannot be replaced by $\hat{T}_{suct}$, since $\hat{T}_{suct}$ is dependent of T_{disch}. Therefore, the alternative model of the part of the four-way valve connecting the air heat exchanger and the compressor was used, see (4.1). In the model based test quantity for the compressor, T_{suct} was replaced with $\hat{T}_{suct\_alt}$ to create a test quantity with estimated inputs.

4.2.3 Test quantities based on the variance of the sensor outputs

To be able to detect if sensors are stuck, test quantities that count the number of times a sensor gives the same output was created. Some of the sensors can give the same output for up to 43 minutes without the sensor being stuck. This is due to the low accuracy of the sensors. Figure 4.10 illustrates a test quantity sensitive to the error Stuck for sensor T_{ref2}. The corresponding threshold is also plotted.

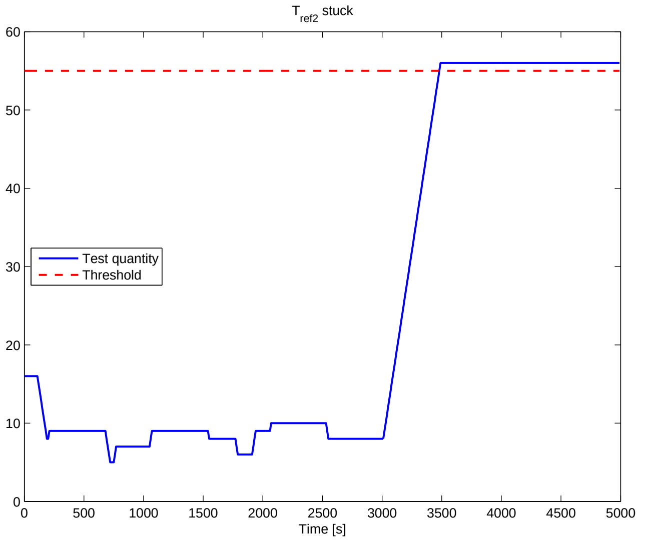

Figure 4.10. Test quantity sensitive to Stuck in the sensor measuring T_{ref2}. At t=2295, T_{ref2} becomes stuck, and 55 seconds later, the test quantity exceeds its threshold.

4.3 Diagnosis algorithm validation

The diagnosis system was tested on the collected sensor data and the data with injected faults. No false alarms arose for the fault free data. For the defection in the sensor measuring T_{ref2}, the diagnosis system gave the diagnosis that the sensor had an offset. However, the sensor did not behave as if it had an offset, the behaviour was indicating bad contact with large variance of the temperature measurements. But this fault mode was not considered in the diagnosis system, and for that reason, the conclusion was that there was an offset.

The result of the tests of the data with injected faults is summarised in Sections 4.3.1 and 4.3.2.

4.3.1 Detectability analysis

For the nine temperature sensors and the two pressure sensors, the fault modes Stuck, Offset, Open circuit, and Short circuit have been investigated. Out of these 44 sensor fault modes, all faults can be detected by the diagnosis system. When it comes to detecting Offset in a sensor, the magnitude of the offset that can be detected differs between the sensors. The detectable (as well as isolable) offset magnitudes have been put together in Table 4.1.

4.3.2 Isolability analysis

An isolability analysis has been made via simulations. It is very straightforward to determine whether or not a sensor is Stuck, Open circuit or Short circuit. These fault modes are all isolable. An offset in any of the pressure sensors cannot be isolated from an offset in the other pressure sensor. An offset in T_{cond_out} cannot be isolated from an offset in T_{cond_in} or T_{ref4}.

Sensor	Detectable offset magnitude	Isolable offset magnitude
Temperature sensor (discharge pipe)	5°C	20°C
Pressure sensor (discharge pipe)	10 bar	None
Temperature sensor (ref 4)	5°C	20°C
Temperature sensor (cond out)	10°C	None
Temperature sensor (cond in)	5°C	10°C
Temperature sensor (ref 3)	10°C	10°C
Temperature sensor (ref 2)	5°C	5°C
Temperature sensor (defrost)	10°C	None
Temperature sensor (ref 1)	5°C	10°C
Pressure sensor (suction line)	5 bar	None
Temperature sensor (suction line)	10°C	10°C

Table 4.1. Offset magnitudes of 2, 5, 10, and 20 were investigated, and the table shows which magnitudes were detectable and isolable.

Chapter 5

Conclusions and future work

This chapter contains a summary of the contributions of the master thesis. It also contains an analysis of how good the result of the master thesis was and suggestions of future work.

5.1 Contributions of the master thesis

This master thesis contributes with a diagnosis system for sensor fault detection and isolation in the studied air source heat pump. The report contains a complete set of models for the components of the refrigerant circuit, where temperature and pressure are the only input signals required. The master thesis is also a good foundation for a further developed diagnosis system, where additional faults can be detected.

5.2 Conclusions

The models that have been chosen for the components are models that are only based on temperature and pressure. This was done because there were no other input signals available. The accuracy of the models were definitely affected by these simplifications since good estimations of the efficiencies (η) were hard to make.

Most of the models of the system are static and quite simple, which is good from a calculation point of view. But when it comes to detecting small offsets (say a couple of degrees) in the temperature sensors, the diagnosis system has some limitations.

For the faults Stuck, Open circuit and Short circuit, the diagnosis system does a good job, since it can detect and isolate all of these fault modes for all the sensors. When it comes to offsets in the sensors, the diagnosis system can detect faults of varying magnitudes, see Table 4.1. This table also shows the possibilities of isolation of the offsets.

It is very promising that offsets are possible to detect for all the sensors, but when considering the control of the heat pump, it is desirable to detect even smaller offsets. For example, if the desired superheat is set to 5°C and the sensor measuring T_{suct} has an offset of the same magnitude, liquid might enter the compressor and destroy it. An offset in the sensor measuring T_{ref2} could make the defrost of the air heat exchanger end before all the ice has melted, which would lower the performance of the heat pump.

Even though it is desirable to detect offsets of smaller magnitude than the ones stated in Table 4.1, it can still be useful to detect the offsets that the created diagnosis system is capable of. Detection of these offsets can, to some extent, prevent damage to components.

5.3 Future work

With access to the actuator signals, the models of the refrigerant circuit can be made more sophisticated. For example, mass flow models and models which take the refrigerant enthalpy into consideration may improve the diagnosis system. This may also make it possible to detect leakage in the system.

Another model improvement could be to consider the phase of the refrigerant with moving interface models of the plate heat exchanger and the air heat exchanger. Apart from (possibly) improving the accuracy of the model, this might also be useful for dimensioning the components, to make sure that the system is as efficient as possible.

The glide phenomenon described in Section 2.2.5 could also be incorporated into the models, since that has influence on the boiling points and the dew points of the refrigerant, which affects the temperature of the refrigerant out of the condenser and the evaporator.

Additionally, models for the refrigerant circuit during cooling production would be useful to have, since this running mode is used extensively during the warmer part of the year. When it comes to defrost mode, models of the refrigerant circuit might not be necessary to improve the diagnosis system, since the defrost lasts for such a short time in comparison to the other running modes. On the other hand, models of the refrigerant circuit during defrost might be useful for other purposes, such as for example optimising the defrost time.

Another improvement could be models of the heat losses in the pipes and components. Furthermore, the receiver and the drying filter might have some influence on the system behaviour, so models of these components could be useful.

With a complete set of models for the system, it is possible to simulate the heat pump. This can be done, in for example Simulink, to be able to predict the behaviour of the system, test new control strategies and optimise performance, et cetera. This can be useful since it can be time consuming and expensive to do the tests on a real system.

Bibliography

[1] Per Andersson. Air charge estimation in turbocharged spark ignition engines. Master's thesis, Linköping University, 2005.

[2] Yunus A. Çengel, Robert H. Turner, and John M. Cimbala. *Fundamentals of Thermal-Fluid Sciences*. McGraw-Hill, third edition, 2008. ISBN 978-007-126631-4.

[3] Michael C. Keir. Dynamic modeling, control and fault detection in vapor compression systems. Master's thesis, University of Wisconsin-Madison, 2004.

[4] Lennart Ljung and Torkel Glad. *Modeling of Dynamic Systems*. Studentlitteratur, second edition, 2004. ISBN 978-91-44-02443-1.

[5] Mattias Nyberg. A generalized minimal hitting-set algorithm to handle diagnosis with behavioral modes. *IEEE Transactions on Systems, Man & Cybernetics: Part A 01/01/2011, Vol. 41 Issue 1, p137-148 12p 10834427*, 2011. ISSN: 10834427.

[6] Mattias Nyberg and Erik Frisk. Model based diagnosis of technical processes, 2010.

[7] Karl Storck, Matts Karlsson, Ingrid Andesson, Johan Renner, and Dan Loyd. Formelsamling i termo- och fluiddynamik, 2010.

[8] Jouko Väänänen. *Models and Games*. Cambridge University Press, first edition, 2011. ISBN 978-0-521-51812-3.

Appendix A

Abbreviations and nomenclature

Abbreviations used in the report can be found in Table A.1 and nomenclature can be found in Table A.2.

Table A.1. Abbreviations

Abbreviation	**Description**
4wv	four-way valve
ahe	air heat exchanger
alt	alternative
amb	ambient
comp	compressor
cond	condenser
disch	discharge (pipe)
exp	expansion valve
MNF	maximal normal form
oc	open circuit
phe	plate heat exchanger
ref	refrigerant
sc	short circuit
suct	suction (line)

Table A.2. Nomenclature

Notation	**Description**
η	efficiency
γ	specific heat capacity ratio
J	threshold
p	pressure
t	time
T	temperature *or* test quantity

Appendix B

Estimated parameters

The estimated parameters for the models are given in Table B.1.

Table B.1. Estimated parameters

Parameter	Estimated value
$a_{1,comp}$	$6.22 \cdot 10^{-3}$
$a_{0,comp}$	1.20
$a_{1,exp}$	-0.19
$a_{0,exp}$	0.42
C_{phe_ref}	1.06
a_{1,phe_water}	$-4.87 \cdot 10^{-3}$
a_{0,phe_water}	0.32
C_{ahe}	4
$a_{1,4wv\_suct}$	$2.42 \cdot 10^{-4}$
$a_{0,4wv\_suct}$	$5.55 \cdot 10^{-3}$
$a_{1,4wv\_disch}$	$7.36 \cdot 10^{-4}$
$a_{0,4wv\_disch}$	$-7.91 \cdot 10^{-3}$
$a_{1,4wv\_suct\_alt}$	$-8.83 \cdot 10^{-3}$
$a_{0,4wv\_suct\_alt}$	-0.54
τ_{ref1}	100
τ_{suct}	100
τ_{disch}	100