

PROPANE HEAT PUMP WITH LOW REFRIGERANT CHARGE – A SIMULATION BASED DESIGN

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Abstract: In the past the so called flammable refrigerants have already been used in heat pumps, but due to a low customer acceptance and a lacking support on the part of the compressor manufacturers most heat pumps have been shifted to conventional refrigerants. Reduced requirements on deployment for refrigeration cycles and heat pumps with refrigerant charges less than 150 g and the availability of first samples of cheap compressors for fridges and freezers with a higher cooling capacity (> 2 kW) made the production of small heat pumps using propane as refrigerant interesting again.

Based on these conditions an exhaust air heat pump with a heating capacity of 2 kW for space and tap-water heating has been designed.

To achieve a shorter developmental period the heat pump has initially been set up as a simulation. Modelica has been chosen as simulation environment using the refrigeration library TIL. Having a co-simulation with LabVIEW it has even been possible to implement complex control algorithms.

The test results of a "real" heat pump that has been set up based on simulation results will be compared to the simulation results of the different levels of development of the refrigeration library.

Key Words: *propane, simulation, low refrigerant charge*

1 INTRODUCTION

In the common discussion on the greenhouse effect, on possibilities of reducing the emission of CO_2 , on renewable energies and on the rising energy costs heat pumps are mentioned more and more.

Having a COP of 3 and more heat pumps are a suitable option to reduce the CO_2 emission and save money due to a lower demand of primary energy.

Using the so called natural refrigerants instead of the nowadays mostly used hydrofluor-carbon refrigerants (HFC) the GWP of refrigerants leaking out of heat pumps and cooling devices could be reduced from up to 1725 (R410a) down to 3 (R290, R600a).

To satisfy the different demands of the customers a fast and efficient way of designing a heat pump is needed. The simulation aided design offers the opportunity to save time and money during the development process and to choose the most efficient setup of the heat pump. Even complex control algorithms can be tested without spending time and money on setting up different heat pump prototypes.

Having a co-simulation of Modelica and LabVIEW it has even been possible to implement complex control algorithms, which enable stable operation having a minimal superheating in every operating point and maximum utilization of the evaporator. Another goal of the controller is to minimize the defrosting time and cycles.

The LabVIEW based simulation of the controller offers another advantage, applying a few modifications it could control a heat pump prototype.

Due to a heating capacity of 2 kW and a higher COP in the space heating mode compared to the one in the tap water heating mode this exhaust air heat pump using propane as refrigerant is very well applicable for zero energy houses with a lower hot tap water demand.

2 PROPANE AS REDRIGERANT

In the past the so called flammable refrigerants have already been used in heat pumps, but due to a low customer acceptance and a lacking support on the part of the compressor manufacturers most heat pumps have been shifted to conventional refrigerants as R134a, R404a and R407c.

With the availability of first samples of cheap compressors for fridges and freezers with a higher cooling capacity (> 2 kW) and reduced requirements on deployment for refrigeration cycles and heat pumps (DIN EN 378-1, DIN EN 60335-2-40) with refrigerant charges less than 150 g the production of small heat pumps using propane as refrigerant got interesting again.

Using propane as the working fluid offers numerous advantages:

- lower system pressures compared to CO_2
- use of existing components or simple and little modifications of existing components
- natural occurrence: high availability, cheap, no costly disposal
- non-toxic (classification A3)
- GWP of 3

And some disadvantages:

- flammability
- sufficiently sized deployment area (DIN EN 378-1, DIN EN 60335-2-40)
- need of encapsulated electric components
- avoidance of the formation of an explosive gas-mixture

3 PROPANE HEAT PUMP SYSTEM

To satisfy the user's demands the heat pump has to run in two different operating modes, the tap water and space heating mode.

Operating in space heating mode water is heated up from $25\text{ }^{\circ}\text{C}$ to $35\text{ }^{\circ}\text{C}$. The process of the refrigerant cycle while operating in the space heating mode is cycle A shown in figure 3.

During the operation in tap water heating mode water is heated up continuously from $15\text{ }^{\circ}\text{C}$ to $65\text{ }^{\circ}\text{C}$. So the process of the refrigeration cycle starts with cycle B and ends with cycle C. This means that the condensing temperature ϑ_c rises from $20\text{ }^{\circ}\text{C}$ to $70\text{ }^{\circ}\text{C}$.

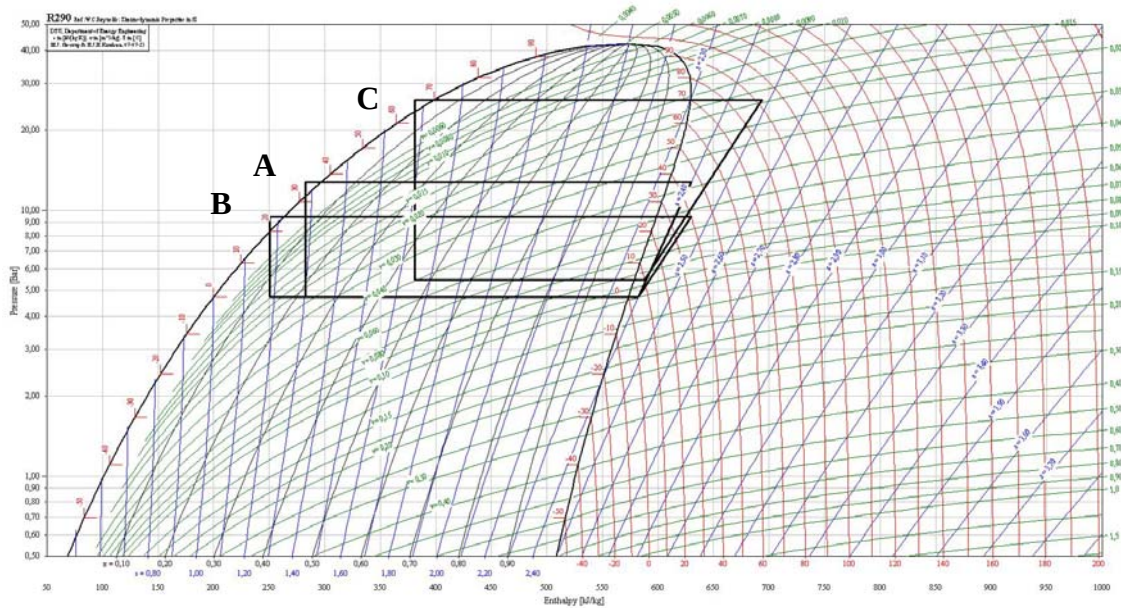


Figure 1: Process of the refrigeration cycle

To enable the switching between the two operating modes tap water heating mode and space heating a water side switching valve is used as shown in figure 2.

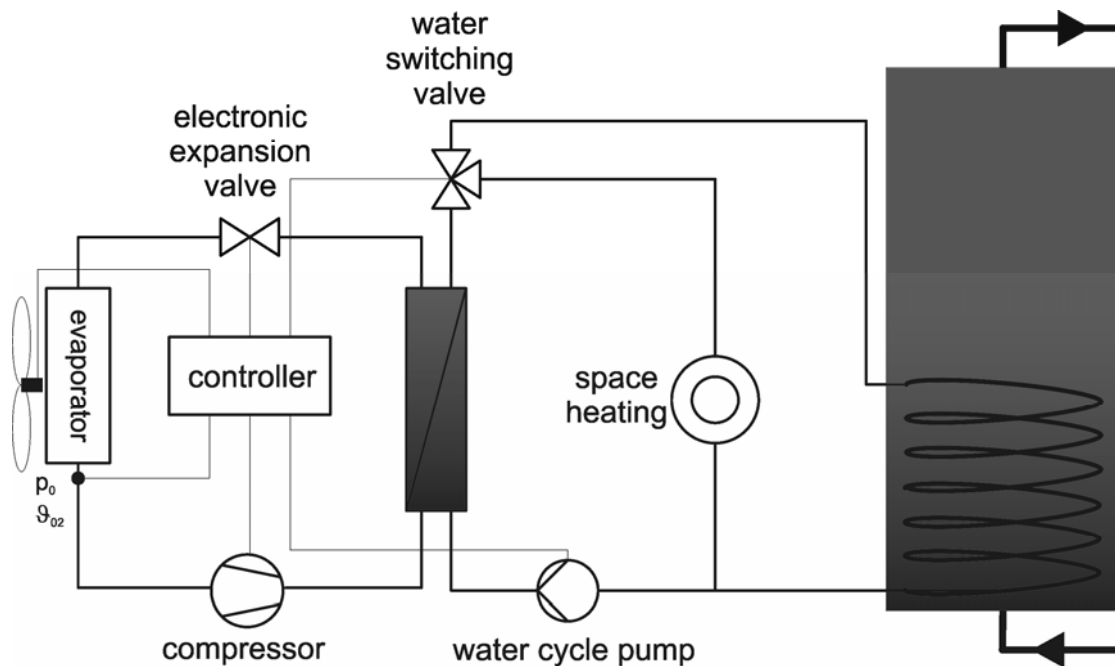


Figure 2: Principle of water hydraulic

4 SIMULATION ENVIRONMENT

4.1 Modelica

The object-oriented modelling language Modelica (Modelica, 2008) has been chosen because Modelica is designed to allow convenient, component-oriented modelling of complex physical systems. The Modelica based refrigerant library TIL (IfT, 2008) maintained by the Institute for Thermodynamics (IfT) at the University of Braunschweig has been chosen instead of the AirConditioning library maintained by Modelon AB (Modelon, 2008) due to its simple and scalable setup.

The component oriented respectively object-oriented design of Modelica and especially the used refrigeration library TIL offer the reuse of components, an easy way of modifying components by the use of modifiers and a simple way of setting up complex system by the combination of individual components.

4.2 LabVIEW

Due to intuitive graphical user interface LabVIEW has been select as development environment to implement the control algorithm. Its graphical dataflow language and block diagram approach naturally represents the flow of data and intuitively maps user interface controls to data, so programmers can easily view and modify data or control inputs.

In this case LabVIEW has been used for control tasks as well as for data acquisition and data visualisation tasks.

To satisfy the demands of both operating modes an advanced control algorithm based on a common PID-controller has been developed. The goal of the controller is to enable the minimal required superheating which offers a stable operation. The favoured value of superheating permits an optimum utilisation of the evaporator and at the same time avoids liquid fluid entering the compressor.

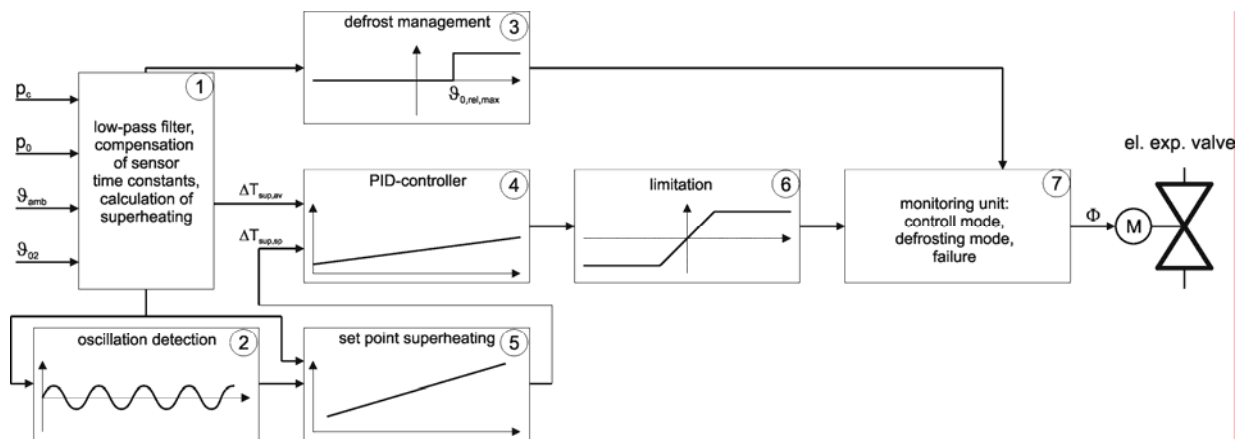


Figure 3: Principle of the heat pump controller

In a first step all input signals are filtered with a low-pass filter and compensated with the sensor time constants. The superheating $\Delta T_{\text{sup,av}}$ is calculated based on the evaporation pressure p_0 and the evaporator outlet temperature q_{02} (1). Based on the oscillation detection signal (2) and refrigeration cycle data the superheating set point $\Delta T_{\text{sup,sp}}$ is calculated (5). The PID-controller (4) assures a fast and exact control of the superheating. Depending on the operation mode the limited signal (6) will be passed through the monitoring unit (7) to the electronic expansion valve. The output signal is the opening ratio Φ of the electronic expansion valve. Details of the defrost management (3) will be explained in the next chapter.

4.3 TISC Server

To connect both software components of the simulation the TLK Inter Software Connector TISC (TLK, 2008) has been used. During a co-simulation TISC manages the setup of the simulation programs, models and parameters.

It exchanges data between the programs, synchronizes and handles events and visualizes the exchanged data.

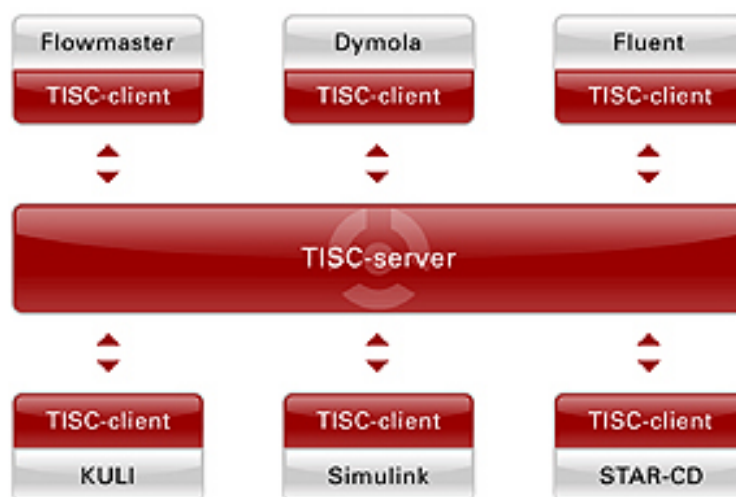


Figure 4: Scheme of the connection server

5 FIRST SETUP OF THE HEAT PUMP SIMULATION

As mentioned in the introduction an exhaust air heat pump with a heating capacity of 2 kW has been set up. Having an air flow rate of 250 m³/h at a temperature of 20 °C and a relative humidity of 40 % the air flow meets the conditions of a zero energy house. The COP has been evaluated for both operating modes, the space heating mode heating up water from 25 °C to 35 °C and the tap water heating mode heating up water from 15 °C to 65 °C. The superheating has been set to 4 K in both modes. Figure 5 shows a first setup of the simulated heat pump.

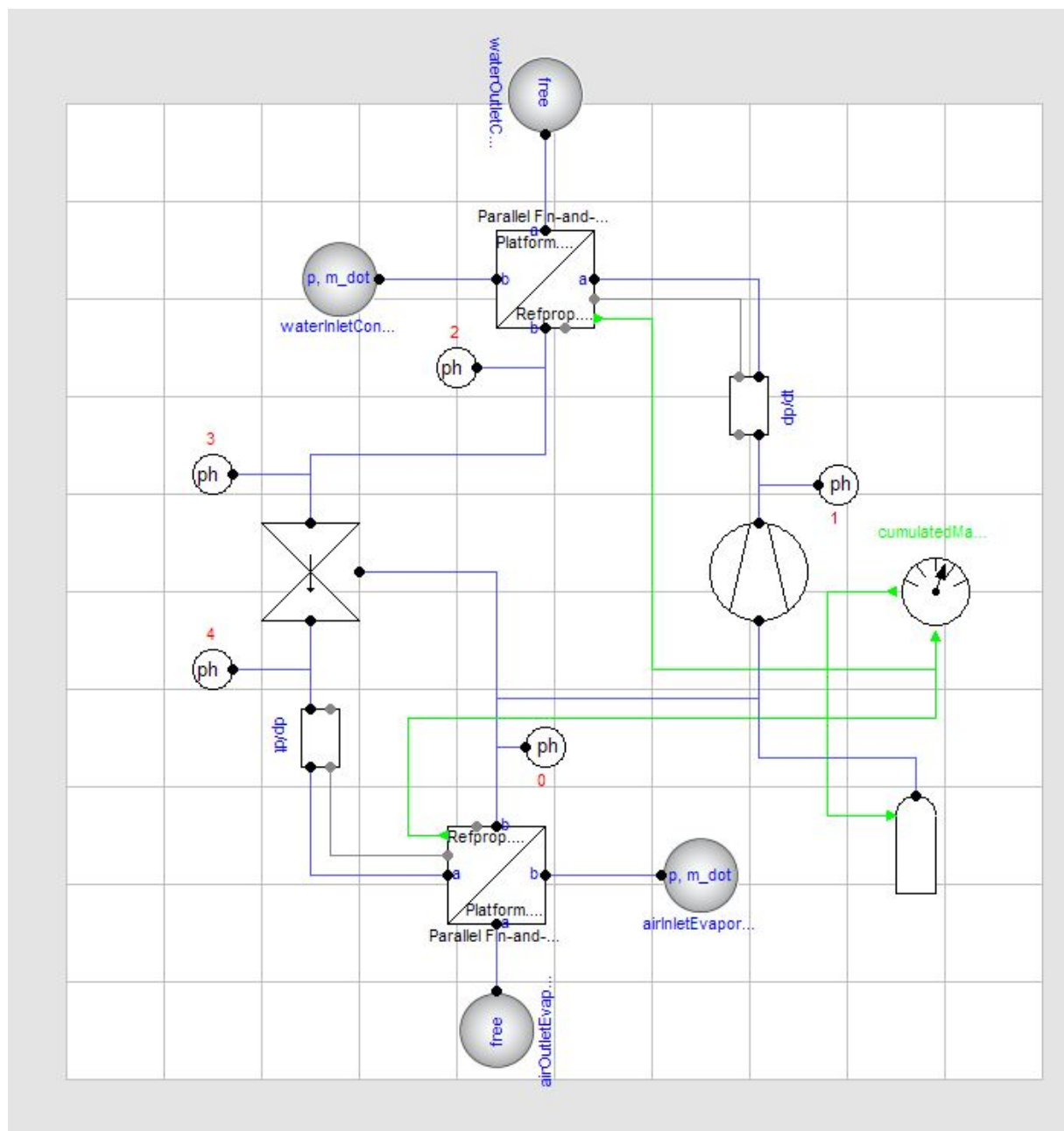


Figure 5: First setup of the simulation

Due to a missing model of the water storage tank an overall COP for the operation in the tap water heating mode could not be evaluated.

Figure 6 shows the trend of the COP during the operation in both modes. While operating in the space heating mode the heat pump achieves a COP of 4,7 having a water inlet temperature (COP_{sp1}) of 25 °C and a water outlet temperature (COP_{sp2}) of 35 °C at the condenser. During operation in the tap water heating mode the COP decreases from 6,69 at a condenser's water inlet temperature (COP_{tw1}) of 20 °C and an outlet temperature (COP_{tw2}) of 24,5 °C down to 2,22 having a water inlet temperature of 65 °C and a water outlet temperature of 68,8 °C.

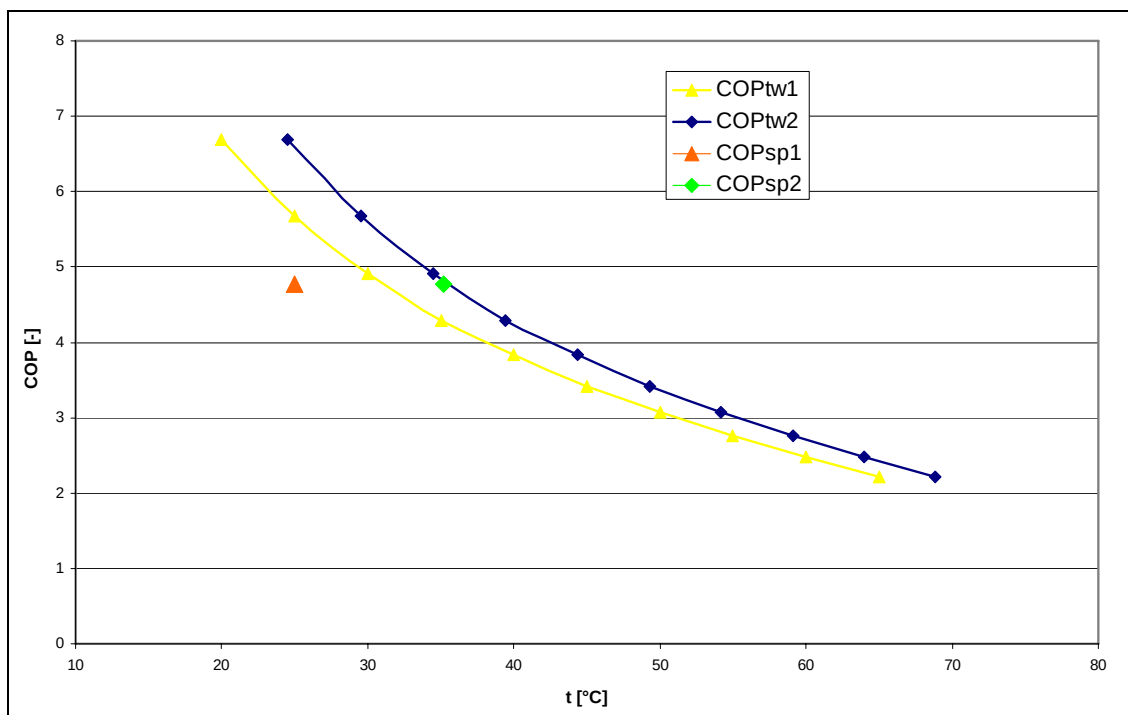


Figure 6: COP of the first simulation setup

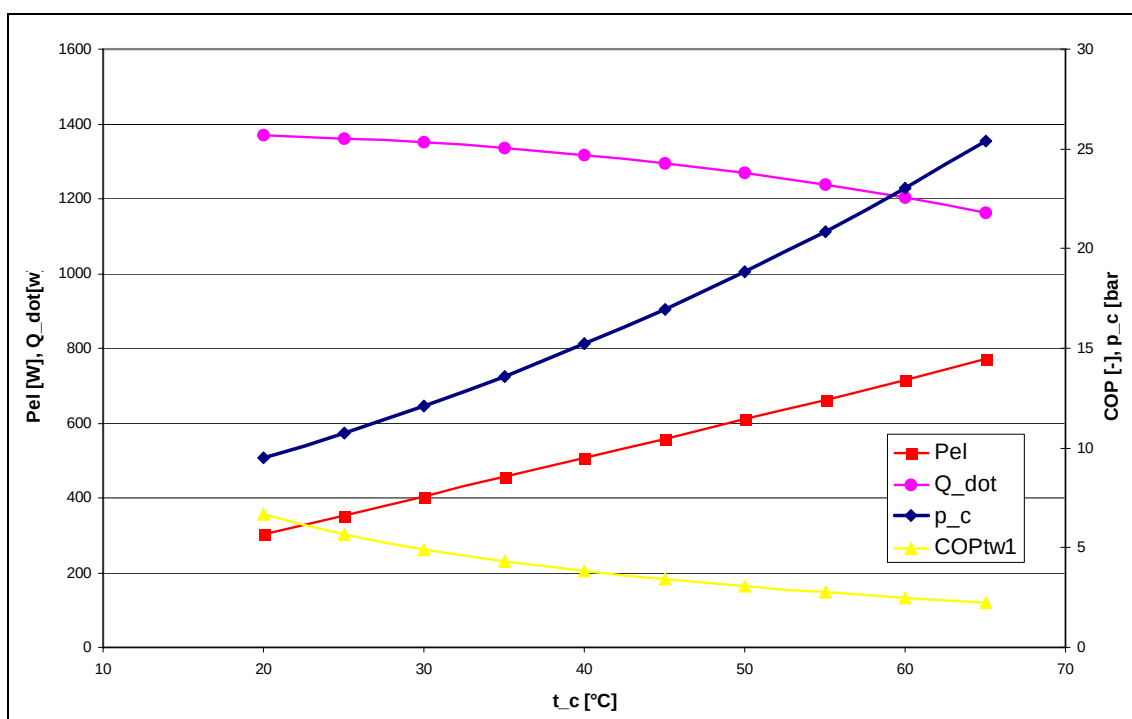


Figure 7: Refrigerant data vs. condensing temperature t_c

As Figure 7 shows, the COP lowers while the condensing temperature t_c rises, this results out of a rising condensing pressure p_c which causes a lower heating capacity $\dot{Q}$ and a higher power consumption P_{el} .

6 IMPROVED SETUP OF THE HEAT PUMP SIMULATION

The latest version of TIL used for the 'improved' second setup comprises some technical innovation in the moist air handling. The most significant changes have been made by adding the components for an enhanced water side simulation. Models of the tap water storage tank, the water pumps and a plate heat exchanger have been added.

In a next step water side switching valves will be implemented which enable a continuous simulation of the tap water and the space heating mode.

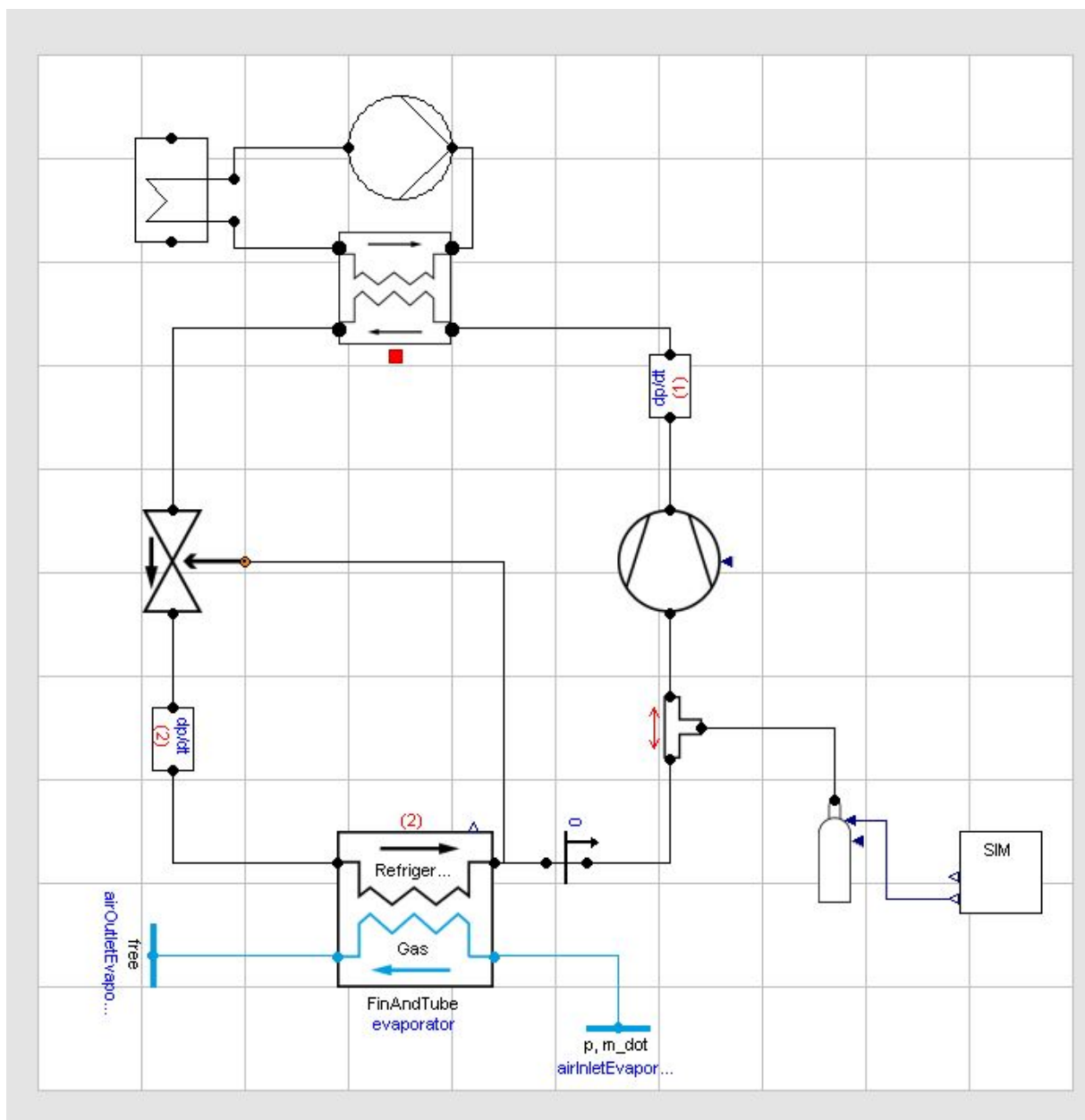


Figure 8: Improved setup of the simulation

Adapting the volumetric and the isentropic efficiency to the correct values which haven't been available during the first simulation Figure 7 shows the trend of the COP during the operation in both modes. While operating in the space heating mode the heat pump achieves a COP of 4,7 having a water inlet temperature (COP_{sp1}) of 25 °C and a water outlet temperature (COP_{sp2}) of 35 °C at the condenser. During operation in the tap water heating mode the COP decreases from 4,23 at a condenser's water inlet temperature (COP_{tw1}) of 20 °C and an

outlet temperature (COP_{tw2}) of 24,7 °C to 1,74 having a water inlet temperature of 65 and a water outlet temperature of 69,2 °C.

The overall COP for heating up the water storage tank from 15 °C to the switch off temperature of 60 °C is 2,7. Due to a temperature difference between the evaporator condensing temperature and the tap water temperature in the dome of the tap water storage tank of 5 K a maximum condensing temperature of 65 °C will be reached till the heat pump will be switched off. Depending on the positioning of the temperature sensor in the water storage tank the temperature difference could rise up another 5 K.

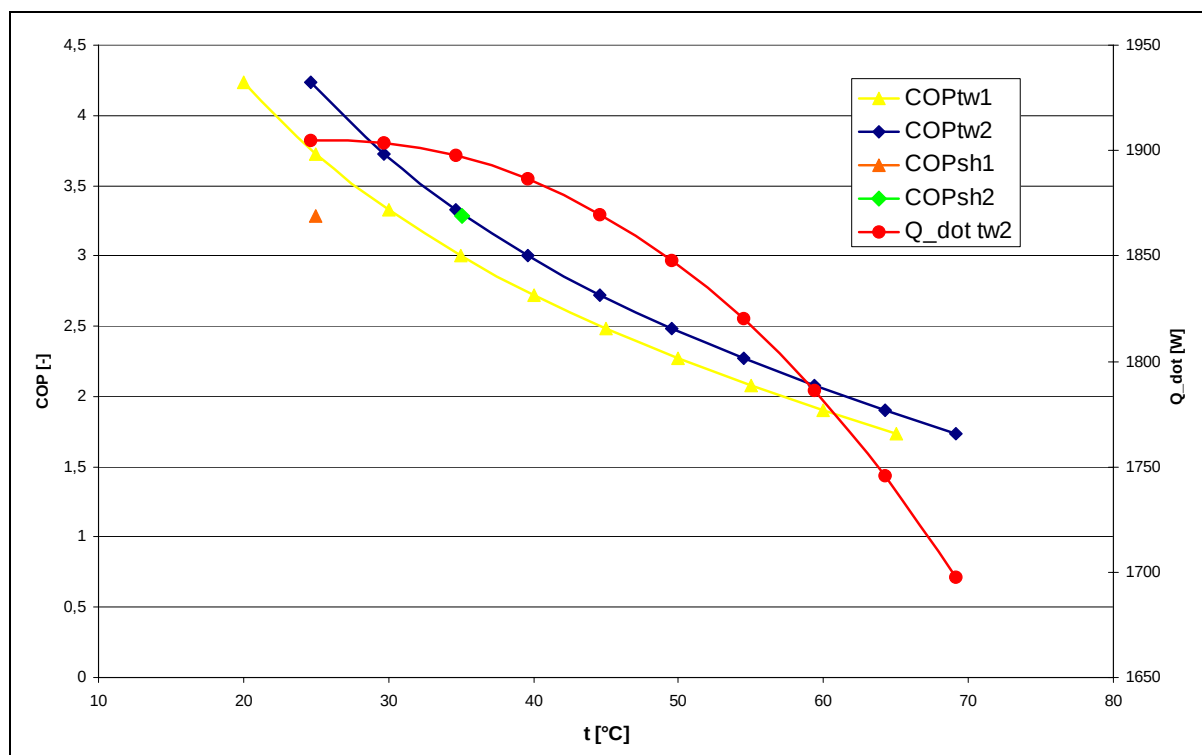


Figure 9: Trend of COP

In the second simulation the superheating had to be raised to 7 K due to stability condition, compared to a superheating of the first simulation of 4 K. With the previous set value of a superheating of 4 K the condensing temperature oscillates with a peak-to-peak signal of 3,5 K. Usually the LabVIEW based control algorithm would raise the superheating to a level that enables stable operation. But in order to achieve a better comparability of the simulation and the later built heat pump prototype the superheating has been set to a fixed value of 7 K for all operating points.

Otherwise the controller might lower the superheating to an optimal value that enables stable operation, which permits an optimum utilisation of the evaporator and at the same time avoids liquid fluid to enter the compressor but complicates the comparison

7 HEAT PUMP PROTOTYPE

Figure 10 shows the run of the COP for different refrigerant charges.

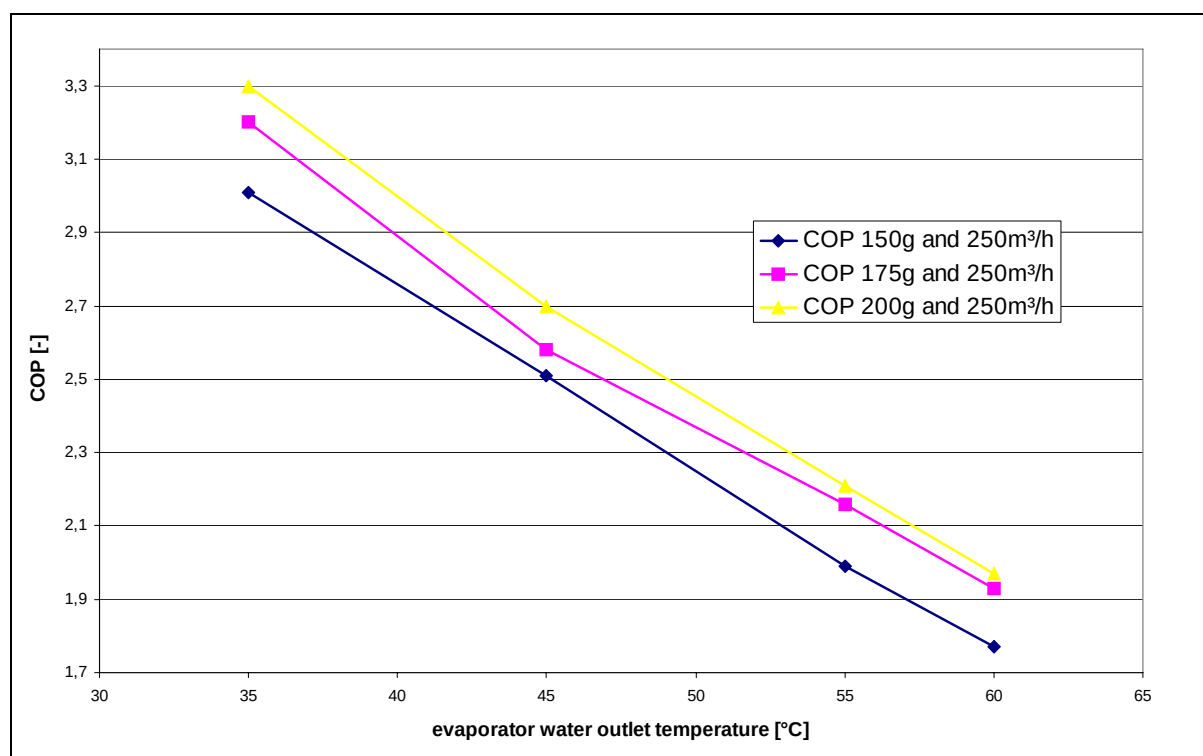


Figure 10: Trend of COP

8 DISCUSSION

As already mentioned in the introduction this heat pump concept having a heating capacity of 2 kW is very well suitable for zero energy houses. Due to a low COP while operating in the tap water mode a propane exhaust air heat pump is especially suitable for households with a low water demand.

The used simulation environment has been an appropriate tool to set up the simulation of the heat pump cycle in a fast and simple way. The acquired data is much more detailed than the data that simple simulation programmes such as CoolPack (DTU, 2000) offer. The object oriented design (Merz, 2002) design offered by Modelica and especially the used library TIL enable the reuse of components and submodels and the option to realise even complex systems.

The applied control concept could be easily adapted to the heat pump prototype.

A comparison of the data presented in figure 9 and 10 shows only some smaller deviations, which result from still existing differences between model and reality.

Table 1 shows a big difference between the simulation's tap water heating COP and the one of the prototype, this results out of a different heat exchanger design in the water storage tank. Due to time limits only a water storage tank having a heat exchanger covering the full height could be surveyed, having a low levelled heat exchanger the COP should achieve a higher level.

Table 1: COPs of R290 heat pumps

	R290 first setup	R290 second setup	R290 prototype
Space heating 25 °C -> 35 °C	4,7	3,28	3,3
Tap water heating 15 °C -> 65 °C	-	2,7	1,6

NOMENCLATURE

COP	Coefficient of Performance	(-)	Subscripts
p	pressure	(bar)	amb ambient
P_{el}	el. power consumption	(W)	c condensing
Q	heat flow	(W)	av actual value
t	temperature	(°C)	sp set point
ΔT_{sup}	superheating	(K)	0 evaporation
ϑ	temperature	(°C)	1 inlet
Φ	opening ratio of electronic expansion valve	(%)	2 outlet

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