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Simulations and experiments on a Solar-Assisted Heat Pump Water Heater

a comparison between R22 and R290 as
working fluid

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1. Preface

Worldwide buildings currently accounts for one-third of all final energy consumption and more than half of the world electricity consumption. Choices made by governments and industry regarding energy efficiency, future energy supply, fuel feedstook, and building energy efficiency standards will ultimately decide the path for energy use in the future. This preface will highlight some findings in global energy trends and energy effciency from IEA's World Energy Outlook (WEO) 2015 followed by a short summary of the Montreal Protocol .

WEO 2015 puts forward three scenarios for energy usage in the future; Current Policies, New Policies, and 450[1] Scenario. The energy demand estimations of each scenario can be viewed in figure 1.1. Current Policies assumes no new policies and a trajectory in line with +10% above the the New Policies Scenario. The New Policies Scenario accounts for existing policies and planned policies and assumes an average increase in energy demand of 1.1 % per year. In the 450 scenario the demand grows only by 0.6 % per year. The 450 scenario assumes new policies limiting the rise of global mean temperature to 2 degrees Celcius above pre-industrial levels, also known as the "Two Degree Goal". Choices to make the future energy system less energy intensive can be motivated by globally shared challenges as climate change or security of energy supply from places like the Middle East. Moreover, choices by individual countries like deployment of renewable energy or unconvetional production of oil and gas like in North Americas influence the energy mix of the

[1] A 450 parts per million (ppm) concentration of CO_2 in the atmosphere is believed to cause a 2 degree Celcius rise in mean global temperature.

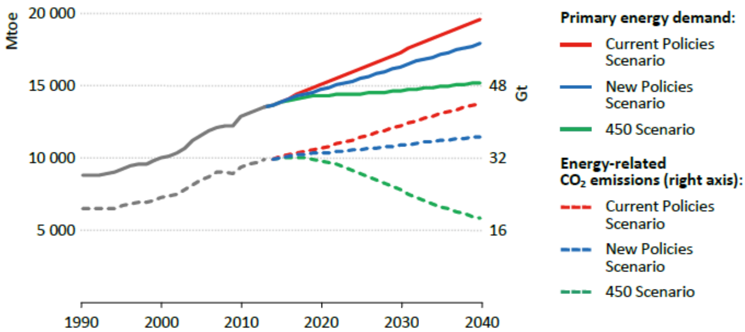

Figure 1.1.: World total primary energy demand and resulting CO2 emissions by scenarios IEA (2015).

future.

Governments will play an important role in determining the evolution and transformation of the global energy sector. WEO 2015 New policies scenario, which IEA believe to be most probable, assumes that fossil-fuel will still be the major primary energy source in 2040. However, investments will move towards renewable energy meaning that for every 1 USD spent on energy investment 60 cents will be invested in renewable. We will also see a decoupling between economic growth and growth in energy consumption due to energy efficency policies and structural changes in the world economy, meaning the global economy will be less energy intensive.

The G20, the 20 largest economies in the world by gross domestic product (GDP), have committed to "rationalize and phase out over the medium term inefficient fossil fuel subsidies that encourages wasteful consumption.". World wide fossil-fuel subsidies were estimated to 493 billion USD in 2014 compared to 390 billion USD in 2009. Though there have been a change in policies in the period the demand for fossil fuel have increased the total spending on subsidies. To ensure a further reduction in fossil fuel subsidies following drivers can be pointed out:

1. **Budgetary pressure:** Subsidies will become a major fiscal burden for governments if fossil fuel consumption grows and

subsidies are not reduced.

2. **Lower international prices:** If projected oil prices are believed to be low in the longer run there is a reduced need for subsidies.

3. **Peer pressure:** G20 and Asian-Pacific Economic Cooperation (APEC) can enforce peer pressure on their respective members to reduce fossil-fuel subsidies.

4. **Policy advice and technical assistance:** Highlighting the potential downstream cost of fossil fuel subsidies like increased pollution, reduced implementation of less harmful techonologies, and reduced energy security, can make governements policy makers move away from fossil fuel subsidies.

5. **Loan conditionality:** Demanding subsidy reform as a condition for loan can also force change. As an example, International Monetary Fund (IMF) demanded increased prices for distric heating and natural gas in Ukraine in March 2015 as condition for loan.

Global energy intensity, a metric to measure the required energy to produce 1 unit GDP, went down 2.7% in 2014 both due to energy efficiency and structural changes in the world economy. Half of the energy efficiency savings are attributed to industry and followed by savings in the transportation sector. Energy consumption grew 0.7% in 2014 and was projected to 2.1% without energy efficency measures. Energy efficiency regulation will play an important role in moving to a less energy intensive future. China have through programs as Top-1000 Energy-Consuming Enterprices Program (later Top 10 000 Program) and the Ten Key Projects (financial incentives for energy savings) managed to save 84 Mtoe[2] of energy demand in the steel sector in the period of 2004-2014. Further, China seeks to reduce local air pollution through phase-out of inefficient coal-fired boilers. In the new policies

[2]Million Ton Oil Equivialent

scenario, energy efficiency is the main reason for decoupling between economic growth and energy demand growth. Efficiency regulations implemented in the building sector, the transport sector, and the industry sector will be the main drivers. It is further projected that the largest savings due to energy efficiency will happen in China due to introduction of CO2-pricing, full implementation of industrial energy performance standards and more stringent energy building codes.

Montreal Protocol on Substances That Deplete the Ozone Layer (Montreal Protocol) is an international treaty first adopted in 1987 with the aim to regulate the production and use of chemicals that contribute to the depletion of the Earth's ozone layer. Currently, nearly 200 countries have signed the Montreal Protocol. Initially the agreement was designed to reduce production and consumption of several types of CFCs and halons by 80 percent of 1986 levels in 1994 and 50 percent of 1986 levels in 1999. Over time, the agreement has been amended to further reduce and completly phase-out CFCs and halons and futher include other substances such as carbon thetrachloride, hydrofluorocarbons (HFCs), hydrocholorofluorocarbons (HCFCs), hydrobromofluorocarbons, methyl bromide, and other ozone depleting chemicals. The phase-out schedule differ between developed and developing countries, and most substances are already phased out in both developing and developed countries. The remaining phase-out of HCFCs is set to 2030 and 2040 in developed and developing countries, respectively. HFCs have not a yet a phase-out date. Scientists contend that the earlier man-made damage to the ozone layer eventually will recover and note that the success of the treaty is exclusively repsonsible for the substansial decrease of decrease in ozone depleting chemical availible for realease into the atmosphere. Britannica (2015)

The Montreal Protocol is a clear example of how an international agreement can give desired long-term results and should be a inspiration of how we can handle other problems facing humanity. The Montreal

Protocol is clear and direct in its targetting and might be one of the reasons for its past success.

Still the use of HFCs contribute to the global warming and investigations into natural refrigerants might, finally, provide the world with less harmful heating and refrigeration technologies.

2. Acknowledgement

I would like to thank professor Yanjun Dai for guiding me through the process of writing my master thesis and helping me conducting experiments.

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Jinfeng Chen was a valuable discussion partner and always helped out when I needed support with experiments or any kind of feedback. Jiang Chengyang should also be thanked helping me set up the experiments on the Solar-Assisted Heat Pump.

My co-students at Green Energy Laboratory room 209 should also be thanked for providing a great work atmosphere and also making sure that I recieved chinese language and customs through a diffusion or osmosis process.

I would like to thank Truls Gundersen for writing a letter of reccomentation. Having the experience to go to China and study has been one of the most wonderful experiences of my life.

3. Summary

3.1. In English

As a larger share of the world population is gaining a higher living standard and a higher energy consumption, it is increasingly important to find new, better, and more efficienct ways to meet our energy demands. A solar-assisted heat pump water heater is one way to efficiently use solar energy to produce hot water for dometic demands. There are currently few commercial applications of this technology and it has remained an idea since it was first porposed in 1955. Solar assisted heat pump can achive elevated evaporator temperature compared to a air-source heat pump and be more efficient when solar radiation is present. It also has the advatage of using a refrigerant as fluid and not water and problemes related to frost is eliminated.

This thesis presents a the results from an experiment conducted on a Solar-Assisted Heat Pump Water Heater using R22 as working fluid. Further, a simulation model was built that could load the weather data from experiment and perform a simulation using a refrigerant of choice. The refrigerant data was loaded from the NIST Refpro

p database into a SIMULINK/Matlab model. In this thesis, the simulation compared R22 and R290 as refrigerant. The overall COP for the experiment was 3.39 under overcast conditions and 3.29 under sunny conditions. The simulation predicted a COP of 4.69 and 4.47 for R290 and R22, respectively, under sunny conditions. The simulation model was not validated and it is believed that the refrigerant charge

of R22 was too low during experiments.

It is proposed to better and more targeted research of SAHPs by having a test rig where different key components can easily be changed and it is easy to evaluate performance. Further it is suggested to research SAHP specify operation conditions for SAHPs and how to make it possible for SAHPs to outperform other heating technologies. SAHPs should also be developed with natural refrigerants in mind.

3.2. In Norwegian

Ettersom en større del av verden befolking får en høyere leverstandard og et høyere energiforbruk, blir det enda viktigere å finne nye, bedre og mer effektive måter å møte vår energibehov. En sol-assistert varmepumpe for varmtvann er effektiv måte å utnytte solenergi til å produsere varmtvann for husholdingsbehov. Foreløbig er det få kommerisielle anvendelser av denne teknologien og har i stor grad vært en forskningside siden 1955. Sol-assisterte varmepumper kan oppnå forhøya fordampertemperatur sammenligna med en luftkjølt varmepumpe i perioder med solinstråling. Siden et kuldemedie blir brukt is solfangerfordamperen vil man også unngå problemene med frost i solfangere slik som ved vann.

Denne oppgaven presenterer resulateter fra et eksperiment gjort på en sol-assistert varmepumpe for varmvannsoppvarming ved bruk av R22 som kuldemedie. Videre så ble det laget en regnemodell som tar i bruk værdata som var tilfelle under eksperiment og bruke forskjellige kuldemedier. Kuldemediedata ble hentet ut fra NIST Refprop sin database of lastet inn i en SIMULINK/Matlab modell. R22 og R290 ble sammenlignet som kuldemedie i regnemodellen. Virkningsgrad under experiment ble målt til 3.39 ved overskya vær og 3.29 ved klart vær. Regnemodellen kom frem til en vikringsgrad på 4.69 og 4.47 for henholdvis R290 og R22 når klarværsdata ble brukt. Regnemodellen ble ikke bekreftet og det tenkes at mengden av R22 i den eksperimentelle varmepumpa var for lav slik virkingsgraden ikke var høy nok.

Det er blir foreslått ha en mer målrettet forskning av Sol-assisterte varmepumper hvor for eksempel en test rig kan bygges for å lett teste og kunne bytte ut hovedkomponenter. Videre blir det forslått å spesifisere under hvilke forhold sol-assisterte varmepumper skal kunne utkonkurrere andre varmeteknologier. Sol-assisterte varmepumper bør også utvikles med naturlige kjølemedier i “tankene”.

Contents

1. Preface i

2. Acknowledgement vi

3. Summary vii

3.1. In English vii

3.2. In Norwegian viii

List of Figures 1

List of Tables 3

4. Introduction to master thesis 1

5. Objectives 2

6. Literature review 4

6.1. Introduction 4

6.2. Solar-Assited Heat Pump 5

6.3. Experimental studies on Solar-Assisted Heat Pumps . . 7

6.4. Mathematical models of Solar-Assisted Heat Pump Systems 8

6.5. Refrigerants 9

6.5.1. Natural Refrigerants 10

6.5.2. Consideration for choice of refrigerants 11

6.5.3. R22 as refrigerant 11

6.5.4. Propane (R290) as refrigerant 12

6.5.5. R290 charge according to EU safety standards . 12

7. Where is the research front in the area of work 13

8. Theory of problems looked into 15

8.1. Heat transfer equations at the solar collector 15

8.2. Heat pump cycle 16

8.3. Water tank 18

9. Calculations 19

9.1. Model implementation 19

9.1.1. Weather data 19

9.1.2. Convection 20

9.1.3. Radiation Exchange 21

9.1.4. Heat Pump 21

9.1.5. Water tank 24

9.1.6. Energy dynamics 25

9.1.7. Model output 25

9.2. Calculations of experimental data 26

10. Presentation of results 28

10.1. Weather conditions during experiment 28

10.2. Experimental results 29

10.3. Simulation results 30

10.4. Comparison between simulations and experiments . . . 33

11. Discussions 38

11.1. Suggested improvements of experiments 38

11.2. Suggested improvements in simulations 38

11.3. From a technical and theoretical possibility to a commercial success 39

11.4. Suggestions on how to organize a work group 40

12. Conclusions 41

13. Proposals for further work **42**

Bibliography **44**

A. MATLAB Scripts **47**

A.1. Initialisation script 47

A.2. Property generator 48

List of Figures

1.1. World total primary energy demand and resulting CO2 emissions by scenarios IEA (2015). ii

6.1. The idea of DX-SAHP and T-s diagram for the vapor compression cycle (Chwieduk, 2012) 5
6.2. SAHP and ASHP in log(p)-h diagram from Sun et al. (2014) 6

9.1. Technical drawing of one finned tube collector. The collector has 16 finned tube in total and each is 2200 [mm] long. 21
9.2. Example of weather data implemented in a 1D-Look Up Table block. 22
9.3. Implentation of convection heat transfer in Simulink . 22
9.4. Implementation of radiation exchange in Simulink. . . 23
9.5. Implementation of heat pump subsystem. 23
9.6. Implementation of compressor in Simulink. 24
9.7. Implementation of working enthalpies in Simulink. . . 24
9.8. Implementation of pressure ratio in Simulink. 25
9.9. Implementation of water tank in Simulink. 25
9.10. Implementation of energy dynamics. 26
9.11. Exporting output values from a simulation into mat-files. 27

10.1. Radiation conditions during experiments. 28

10.2. Ambient temperature during experiments. 29
10.3. Ten-minute average wind speed during experiments. . 30
10.4. Compressor power consumption during experiments. . 31
10.5. Water temperature during experiments. 32
10.6. Predicted compressor work from simulations for both R290 and R22. 33
10.7. Predicted condenser effect for both R290 and R22. . . 34
10.8. Predicted pressure ratio for both R290 and R22. . . . 34
10.9. Predicted COP for both R290 and R22. 35
10.10Predicted plate temperature for both R290 and R22. . 35
10.11Predeicted hot water temperature for both R290 and R22. 36
10.12Predicted volumetric efficiency for both R290 and R22. 36
10.13Predicted refrigerant flow for both R290 and R22. . . 37

List of Tables

6.1. Contribution of Gases to the Greenhouse Effect in percent. Hwang et al. (1998) 10
6.2. Environmental Effects of Refrigerants. Hwang et al. (1998) 11

9.1. Physical dimensions and parameters for the simulated Solar-Assisted Heat Pump. 20

10.1. Mean weather conditions during days of experiments . 29
10.2. Results from experiments 30
10.3. Key output parameters from simulation model. 31

Nomenclature

ASHP	Air source heat pump
DX-SAHP	Direct Expansion Solar-Assisted Heat Pump
EU	European Union
GWP	Global Warming Potential
HCFCs	Hydrochlorinefluorocarbons
HFCs	Hydrofluorocarbons
ODP	Ozone Depletion Potential
R1270	Propylene, refrigrant code
R22	HCFC refrigerant Chlorodifluoromethane
R290	Propane, refrigrant code
R717	Ammonia, refrigerant code
R744	Carbon Dioxide, refrigerant code
SAHP-WH	Solar-Assisted Heat Pump Water Heater

4. Introduction to master thesis

Solar-Assisted Heat Pumps utilize solar irradiation to elevate the evaporation temperature and thus improve the performance of a heat pump system. This thesis explores a Solar-Assited Heat Pump Water Heater (SAHP-WH) through simulation and experimental setup. Further, it will explore the potential for R290 (propane) as an R22-alternative. As artificial refrigerant leakage causes a significant contribution to global warming, it is a growing interest to develop heating and cooling technology with natural refrigrants. By comparison, the natural refrigerants are cheap and abduntant, and reduces the environmental impacts due to heating and cooling demands of modern civilication. An early market-entry in emerging economies, like China and India, should not be underestimated and it is of global interest to have this change happening as fast as possible. However, natural refrigrant causes safety concerns in consumer for consumer application. Especially when using hydrocarbons as refrigerants safety regarding flammability is an critical issue. Current EU regulations, EN378, allows for 0.150 $[kg]$ refrigerant charge closed sealed systems and allow for a larger charge dependant on room volume and installation height. This current regulation make a design constraint for consumer heating and refrigeration products for domestic use. But should nevertheless be explored.

5. Objectives

Background and objective

Solar radiation is a free and abdundant energy resource we can "tap into" and help us meet the heating demands of residential buildings. Solar-thermal collectors have been a successful technology deployed in China; however, a Direct-Expansion Solar-Assisted Heat Pump (DX-SAHP) is another approach to utilize the sun to gain more heat in shorter time.

> It is estimated that, in China, solar water heater have been marketed for about 10 billion RMB Yuan each year. It is also reported that China has 5 million solar water heaters installed in families in 2000, and it is still being developed more and more rapidly. In virtue of its advantages over conventional solar water heaters, the DX-SAHPWH is expected to have a giant potential market in China. Li et al. (2007)

The idea of SAHP is old and is not yet a commercial availible. Most SAHPs are custom built and local data for irradation is important to evaluate if it is preferred or not to use. In terms, SAHP Water Heaters have to prove better operations than a convetional Heat Pump Water Heater. Nevertheless, the technology should be explored as an option for water heating and under which circumstances it is beneficial. Since it not yet commercial it should be designed with natural refrigerants in mind to meet future regulations and be environmental friendly.

The following tasks are to be considered:

- Develop a simple simulation model of a Solar-Assisted Heat Pump with real weather data input.
- Compare simulations to experimental setup.
- Compare the use of R22 to R290 in the simulations and experiments.
- Write a paper based on results in master thesis.

6. Literature review

6.1. Introduction

Sporn and Ambrose proposed to integrate solar energy and heat pump technology in 1955, and the field of SAHP have since been in researchers interests. However, solutions entering the consumer market are still few and most SAHPs today are custom built. (Muginer and Hadron, 2013).

Technology Roadmap: Solar Heating and Cooling IEA (2012) estimates that solar collectors for hot water and space heating will reach 3500 $[GW_{th}]$, which corresponds to 14% of the total need, in 2050 . Governements must ensure a succesful deployment through long-term stable frameworks. Different economic incentives must be in place that are both transparent and predictable. Further, all economic incentive schemes should be independant of state budget so a sudden withdrawal of incentives will not destabilize the market.

> "Governments should take a broad perspective when (re)considering their countries' solar heating and cooling potential." IEA (2012)

This review will cover the following topics; solar-assisted heat pump, refrigerants and simulation method. Each section will cover governing concepts and thoughts from relevant literature.

6.2. Solar-Assited Heat Pump

An SAHP uses the solar irradiation to elevate the evaporator temperature and thus increasing the COP of the heat pump system. A heat pump system converting solar irradiation directly via a solar collector-evaporator is termed a direct expansion solar-assisted heat pump (DX-SAHP).

Chwieduk (2012) wrote a comprehensive review explaining the theory and application of SAHPs. He argues that SAHPs can significantly contribute to the reduction of fossil fuel usage and as a result reduce the running costs of a heating system. Further, he notes that a DX-SAHP can have rapid changes in temperature within a day and also seasonal changes. Working fluids of DX-SAHP should be able to have an evaporation temperature of 30 °C in summer and −20 °C in winter. Figure 6.1 shows both the a concept sketch and the T-S diagram for a DX-SAHP. Figure 6.2 gives a clearer idea of the advantage of the SAHP versus an air-source heat pump (ASHP) that would need a lower evaporation temperature when there is solar irradiation present.

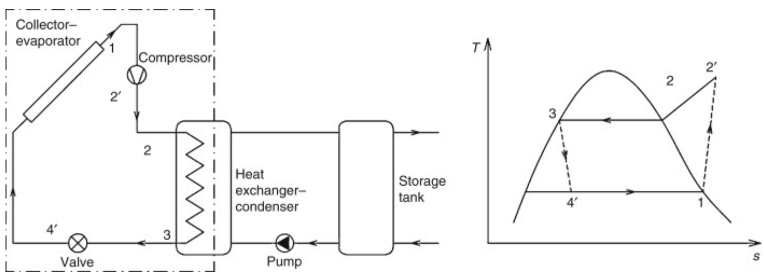

Figure 6.1.: The idea of DX-SAHP and T-s diagram for the vapor compression cycle (Chwieduk, 2012)

Chaichana et al. (2003) conducted a study of natural refrigerants in SAHP systems and points out that R744 (CO_2) can reach temperatures up to its critical point and is therefore not suited for SAHPs. R717 (Ammonia), on the other hand, have a latent evaporative heat 8 times higher than compared to R22 and it does not cause any harm to the

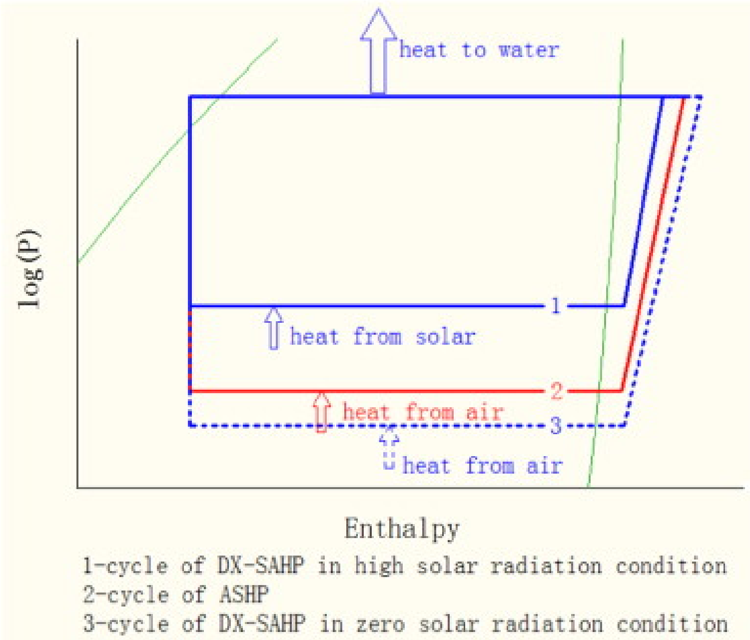

Figure 6.2.: SAHP and ASHP in log(p)-h diagram from Sun et al. (2014)

ozone layer. This reduces the required refrigerant flow and hence reduces the chance for leakage. Concerning the flammability and toxicity, R717 can have a problem entering the consumer marked due to consumer safety concerns, but is still Chaichana et al. (2003) lists R717 as a prime candidate for SAHPs. R290 and R1270 is identified as direct drop in substitutes for R22.

It should also be noted that R717 will corrode copper alloys and a R717-SAHP should could not use copper alloys it in heat exchangers or any other part of the heat pump in contact with the refrigerant. Further, a 15-28% volume fraction in air is required and combustion temperature of 630 °C for the R717 to ignite. R717 have a distinct and sharp smell and can cause panic even i low concentrations. Following general safety procedures there is no problem using R717. (SINTEF, 2001)

6.3. Experimental studies on Solar-Assisted Heat Pumps

Li et al. (2007) set up a SAHP with R22 as working fluid, solar-collector evaporator of 4.20 $[m^2]$, and water tank of 150 $[L]$. A COP of 6.61 was reached when heating water from 13.4 $[C]$ to 50.5 $[C]$ in 94 min with an average ambient temperature of 20.6 [C] and average solar radiation intensity of 955 $[W/m^2]$. The COP was 3.11 at rainy night with an average temperature of 17.1 [C]. Further, it is suggested that the system would heat the same amount of water from 20.6 $[C]$ to 50.0 $[C]$ in 90 minutes with an average ambient temperature of 26.6 $[C]$ and average solar radiation intensity of 709 $[W/m^2]$.

Kuang and Wang (2006) designed a multifunctional SAHP with R22 as working fluid, variable frequency drive compressor, collector-evaporator area of 10.5 $[m^2]$, and an air-source heat exchanger as backup in periods of low solar irradation intensity. The system offered three fundamental operating modes, space-heating, water-heating, and space-cooling mode. Space-cooling mode is achived by a installed four-way valve that let the refrigerant flow in the opposite direction. Experiments were carried out in four months to investigate the different operating modes. In space-heating-mode the system reached a daily-average heat pump COP between 2.6 and 3.3 and a system COP between 2.1 and 2.7.

Chata et al. (2005) analyzed thermal performance of DX-SAHP with R134a, R404a, R410a and R407c to indentify which of those refrigerants that was best suited for SAHP and further develop a graphical procedyre to determine the collector size of a DX-SAHP. R134a was suggested to be the best alternative among the refrigerants.

Cerit and Erbay (2013) investigated how different rollbond collector-evaporator design influenced the performance of a DX-SAHP and thus determine which system worked the best. The working fluid used in the study was R134a and the COP varied from 2.42-3.30 depending on design under equal climate conditions in Turkey.

Panaras et al. (2014) proposed a method called Dynamic System Testing for testing and evaluation of performance of combined solar thermal heat pump hot water systems. The approach can be considered a black box approach and will not demand any internal measurement. Further, they claim that their method for short testing periods makes it possible to predict a long-term performance of a SAHP system with an uncertainty below 10%.

Li et al. (2007) analyzed and compared two DX-SAHP systems using R22 as working fluid and with rated compressor power input of 750 $[W]$ and 400 $[W]$. Since R22 will be phased-out in 2040 in developing countries as China, it is important to investigate the ways to improve these systems. They conduct a exergy analysis of the system and define an optimum evaporation temperature of the collector evaporator as $T_{eva,optimum} = (T_0 T_{sa})^{1/2}$, where T_0 is the ambient temperature and T_{sa} is the solar-air temperature. This temperature is derivative of the exergy efficiency equation of the collector-evaporator. For the weather data during their experiments the average optimum evaporation temperature is found to be 39.1 $[C]$, while the average evaporation temperature from experiments were 19.8 $[C]$. The authors notes that the optimum evaporation temperature might in turn pose problems for compressor exhaust gas temperature being too high.

6.4. Mathematical models of Solar-Assisted Heat Pump Systems

Kong et al. (2011) developed a dynamic model for a solar-assisted heat pump with R22 as refrigerant. A distributed parameter models were used for the solar collector/evaporator and a lumped parameter approach for the comrpessor, thermostatic expansion valve, and model of the refrigerant charge.

Chow et al. (2010) investigated the possibility for a DX-SAHP in Hong Kong with a numerical model with Typical Meterorologial Year (TMY) for Hong Kong as input, They concluded that the system could reach a year-average COP of 6.46. It was assumed a compressor of 1 $[kW]$ rated input power, a 2500 $[L]$ water tank, and an effective heat exhanger area of 12 $[m^2]$ The simulation assumed 2060 working hours per year, corresponding to 5.64 average working hours per day and projected a possiblity to produce a double amount of heat in the summer months compared to the winter months.

Tsai (2015) simulated a PV-SAHP system in the MATLAB/Simulink environment and validated the simulation with real world experiments.

6.5. Refrigerants

Refrigerants are the circulating fluids used in heat pump systems to provide heating, cooling or both. Different refrigerants are used for different applications relating to their thermophysical properties, price or safety regulations. Historically, artificial compounds known as CFCs have been popular compounds due to their thermodynamic performance and properties regarding safety such as; non-toxicity, non-flammablility, non-corrosiveness, and odorlessness. However, CFCs effect the environment in terms of global warming and ozone depletion are now phased-out of production.

The relative contribution to environmental effect is termed Ozon Depletion Potential (ODP) and Global Warming Potential (GWP). The GWP of CO_2 is 1.0 and the GWP and ODP of R12 is 1, a refrigerants GWP or ODP is given relative to the contribution of CO_2 and R12.

Due to the undesired environmental effects of CFC the Montreal Protocol was established to start the phase-out of environmentally harmful refrigerants. As updated versions of the Montreal Protocol will ensure a further phase-out of environmentally harmful refrigerants globally, a renewed interest in so-called natural refrigerants, meaning compounds that circulate naturally in the environment, have become appearant.

6.5.1. Natural Refrigerants

Natural refrigerants are working fluids based on molecules that occur in nature and does not affect the environment in any unknown way. Examples of natural refrigerants are carbon-dioxide, ammonia, hydrocarbons, water, and air. They are gaining more interest since they can provide a long-term solutions to the environmental problems associated with artificial refrigerants. CFCs and HCFCs have a significant impact on contribution to man-made Greenhouse Effect (see. Table 6.1). Also, the GWP for artificial refrigerants outnumber CO_2 by factors in the range of thousands, and further CFCs and HCFCs contribute to ozone depletion (see Table 6.2) . Due to this fact some environmentalists believe the refrigeration industry should by-pass HFCs altogether and employ natural refrigrants as soon as possible. (Hwang et al., 1998)

Ammonia is a popular refrigerant in industry due to good thermodynamic performance; however, ammonia can be toxic and under certain conditions flammable. Though this is the case the odor of ammonia is distinct and self-alarming in far lower concentrations than lethal limits. Measures to ensure safety increases costs Hwang et al. (1998).

Hydrocarbons are refrigerant with excellent thermodynamic qualities, but are also flammable and explosive. Due these risks legality or

Gases	CO2	CH4	N20	O3	CFCs,HCFCs	H20
Man-made gasses (1998)	52	22	16	2	8	-
Natural greenhouse effect	23	2	2	3	-	70

Table 6.1.: Contribution of Gases to the Greenhouse Effect in percent. Hwang et al. (1998)

	Refrigrant	ODP	GWP (100 years)
CFCs	R11	1	3800
	R12	1	8100
HCFCs	R22	0.055	1500
	R32	0.11	650
	R134a	0.065	1300
	R410a	0	1725
Natural Refrigrants	CO2	0	1
	Ammonia	0	0
	Isobutane (R600a)	0	3
	Propane (R290)	0	3

Table 6.2.: Environmental Effects of Refrigerants. Hwang et al. (1998)

regulations regarding hydrocarbons vary. EU's safety standards regarding flammable and toxic refrigerants are elaborated in section 6.5.5. Since the mid-1990s nearly all refrigerator production in Germany has used hydrocarbons Hwang et al. (1998).

6.5.2. Consideration for choice of refrigerants

The choice of refrigrant is determined by several factors, like condensing pressure, pressure ratio, volumetric heat performance etc. The condesing pressure is determined by the components ability maxiumum allowed pressure. Most components are designed for a maximum pressure around 25 bar. The saturation pressure differs between refrigrant. It is also important to ensure a evaporation pressure over the atmospheric pressure so no air and moisture enters the heat pump systems.

Futher, the COP of a heat pump is also closely linked to pressure ratio, being the ratio between condensation and evaporation pressure.

6.5.3. R22 as refrigerant

Historically, R22 have been a dominating refrigrant for heat pumps with moderate temperature demands (<61 [C]). The fluid has high volumetric heat capcity, and thus enables the compressor volume to be 35-40% less than R12 and R500. However, the gas temperature exiting the compressor is higher compared to other halo-carbons and heat pumps with relatively high temperature lifts have been known to decompose oil which in turn have given rise to acid formation and compressor failure. (SINTEF, 2001)

6.5.4. Propane (R290) as refrigerant

R290 have good thermal and environmental properties and are now increasingly being used as refrigerant. However, R290 are highly flammable and explosive and accordingly most suited for small scale heat pump systems with a low refrigerant charge. R290 is relatively similar to R22 and will also have a lower refrigrant charge and working pressures due to its thermal properties.

6.5.5. R290 charge according to EU safety standards

European Union's (EU's) safety standard EN378 regulates the design of heat pump systems for various purposes in various locations. Occupancy is classified into class A, B, and C, which corresponds to general occupancy, supervied occupancy, and occupancy with autorised access only, respectively. Further, the refrigerants are classified according to their flammability and toxicity. R290 is classified as an A3 refrigerant and can be used without limitation as long as refrigerant charge do not exceed 0.15 $[kg]$. The standard also allows for increased charge being calculated $m_{max} = 2.5 \times LFL^{5/4} \times h_0 \times A^{1/2}$ with a maxiumum value of 1.5 kg. In case of, R290 the lower flammability limit is set to 0.038 $[kg/m^3]$ and for a room that ground area of $30[m^2]$ and an installation hight of 1.8 [m] a refrigreant charge of 0.414 $[kg]$ would be allowed (CEN 2008).

7. Where is the research front in the area of work

Most reasearch explores the potential for SAHP for water heating and integration with PV panels and the evaporator of the SAHP. Simulations studies focus heavily on development of accurate physical representation of the experimental SAHP, and some studies focus on the potential for SAHP. Studies often compare SAHPs to heat pump water heaters of solar thermal collector. What is missing in the litterature is the discussion on how to make SAHP a commecial success. If SAHPs are to become a commecial technology customers must be given good reasons to choose SAHPs over other technologies. This argues for a multidisciplinary approach where the market potential is explored, the technology's possibility to meet customer demand, how architects and entrepreneurs have to keep the SAHP as an availible option, and further how governments, on national and local level, can make incentives to ensure a successful deployment of SAHP both in commercial and energy efficient terms.

SAHP is a technology that needs to evaluated in terms of potential at a given location and further developed with potential customers in mind. Residential customers needs reasons to believe that a SAHP will be a good investment over other technologies. Comparatively, a heat pump water heater is easy to install and solar-assisted heat pump will probably be more expensive to manufacture and install. If this fact is to change local policies should give some kind of payback ensuring

SAHPs to be used if it is from an environmental perspective and not neccessarily a economic perspective better to use.

In IEAs Solar Heating and Cooling Roadmap it is suggested to develop commercial small size kit systems with an overall electrical COP of 5 within 2012-2020.

8. Theory of problems looked into

The problem treated in this thesis consist of a normal vapour-compression cycle heat pump with solar thermal collector-evaporator. Tsai (2015) paper “Modeling and validation of refrigerant-based PVT-assisted heat pump water heating (PVTA-HPWH) system” inspired for the problem-solving approach and theoretical foundation.

8.1. Heat transfer equations at the solar collector

The governing energy balance equation for the solar collector used is the following equation:

$$\frac{dE}{dt} = m_{plate}c_{plate}\frac{dT_{plate}}{dt} = Q_{solar} - Q_{rad} - Q_{conv} - Q_{evap} \qquad (8.1)$$

where m_{plate} is the mass of the solar collector in $[kg]$, c_{plate} is the specific heat capacity of the solar collector in $[J/kgK]$, $\frac{dT_{plate}}{dt}$ is the rate of change in temperature in the solar collector in $[K/s]$, Q_{solar} is the absorbed solar radiation in $[W]$, Q_{rad} is the radiation exchange with the sky in $[W]$, Q_{conv} is the convection heat transfer in $[W]$, and Q_{evap} is the effect from the heat pump evaporator in $[W]$ (see section 8.2). The mathematical representation assumes heat transfer in and out of the collector-evaporator where the collector temperature is assumed to be uniform. The initial conditions for $T_{plate}$is the ambient air temperature.

The solar energy absorbed by the system is assumed to be the following:

$$Q_{solar} = \alpha G A_{plate-solar} \tag{8.2}$$

where α is the absorbtivity of the plate a dimensionless parameter, G is the incomming radation in $[W/m^2]$, and $A_{plate-solar}$ is the collector area being exposed to solar radation in $[m^2]$.

$$Q_{rad} = \sigma \varepsilon_{plate}(T_{plate}^4 - T_{sky}^4)A_{evap-solar} \tag{8.3}$$

where σ is Stefan-Boltzmann's constant equal to $5.67{\times}10^{-8}[Wm^{-2}K^{-4}]$, ε_{plate} is the emissivity a dimensionless parameter, and T_{plate} is the temperature of the plate, $T_{sky} = 0.0552T_{amb}^{1.5}$ in [K].

The convective heat transfer is modelled in the following way:

$$Q_{conv} = h_{conv}(T_{plate} - T_{amb})A_{plate} \tag{8.4}$$

where h_{conv} is the convective heat transfer coefficient to the ambient air and T_{amb} is the ambient temperature. Convection heat transfer for flat plates solar thermal collectors with less the 0.5 meters length from Sartori (2006) and approximated by the following empirical relation:

$$h_{conv} = 5.7 + 3.8V_{wind} \tag{8.5}$$

where V_{wind} is windspeed in $[m/s]$

8.2. Heat pump cycle

The evaporative effect is determined by the state points of the thermodynamic cycle and refrigeratnt mass flow and is implemented in the following way:

$$Q_{evap} = m_{refrig}(h_1 - h_4) \tag{8.6}$$

where m_{refrig} is the refrigerant mass flow rate in $[m/s]$ and h_1 and h_4 are the thermodynamic state points for the evaporator side of the heat pump.

Equally, the condenser effect is implemented as:

$$Q_{cond} = m_{refrig}(h_2 - h_4) \tag{8.7}$$

where h_2 and h_4 are the thermodynamic state points of the condenser side of the heat pump. And finally the compressor effect is implemented as:

$$W_{comp} = m_{refrig}(h_2 - h_1) \tag{8.8}$$

where h_1 and h_2 correspond to the inlet and outlet of the compressor respecitvely. Refrigerant mass flow rate is defined by the following equation:

$$m_{refrig} = \frac{NV\lambda(\pi)}{v_1} \tag{8.9}$$

where N is the constant rotational speed of the compressor in rotations per second, $[rps]$, V is the clearance volume of the compressor in $[m^3]$, $\lambda(\pi)$ is the volumetic efficiency dependent on pressure ratio $\pi = p_2/p_1$, and v_1 is the specific volume at state one of the heat pump cycle in $[m^3/kg]$.

$$\lambda(\pi) = 1 - \Phi_0(\pi^{1/\kappa} - 1) \tag{8.10}$$

where $\kappa = c_p/c_v$ for the refrigerant and Φ_0 is clearance volumetric fraction of the compressor. This formula is found in Koelet (1992).

8.3. Water tank

The water tank model assumes that all the heat rejected by the condenser is accumulated in the water tank and further treats the water mass in the tank as one uniform body with the same temperature.

$$\frac{dE}{dt} = m_w c p_w \frac{dT}{dt} = Q_{cond} \tag{8.11}$$

9. Calculations

The MATLAB/Simulink environment offers an easy-to-use framework for modelling mathematical and physical problems. Simulink is a dynamic simulation tool that utilize the MATLAB workspace to load parameters and other data sets. A workspace can easily be defined by a M-script and those used in this thesis can be viewed in Appendix A. Further, the model uses different blocks from the Simulink Model Library to build the equations from chapter 8.

9.1. Model implementation

The Simulation model built simulink loads weather-data parameters into a sub-subsystem called "solar-assisted heat pump". A clock function syncronizes the weather data of the simulation period. The unit of time chosen for simulation is seconds and one "run" where 1 hour corresponds to 3.600 seconds. The weather data is obtained from measurement equipment at the roof of Green Energy Lab (GEL) at SJTU consisting of temperature, solar radiation, and wind data logged every 5 minutes. The following subsections will describe the implementation of each component. Model parameters can be viewed in table 9.1 and figure 9.1 shows the technical drawing of the solar thermal collector.

9.1.1. Weather data

Weather data is imported from a EXCEL datasheet and made into a MATLAB mat-file to store the values. A mat-file to store the time

Parameter	Value
absortivity	0.94 $[-]$
emissivity	0.2 $[-]$
solar collector area	2.2×0.8 $[m^2]$
convection area	$2.2 \times 2 \times (16 \times 0.06)$ $[m^2]$
specific heat collector	0.9020 $[kJ/kg - K]$
mass evaporator	9 $[kg]$
thermal mass water tank	150×4200 $[kJ/K]$
isentropic efficiency	0.75$[-]$
rotational speed compressor	2860 $[rpm]$ = 2860/60 $[rps]$
piston displacement	7.4×10^{-6} $[m^3]$

Table 9.1.: Physical dimensions and parameters for the simulated Solar-Assisted Heat Pump.

point for the weather data is made to store each value with 5 minutes or 300 seconds interval. These files are loaded into the MATLAB workspace via a M-script and the table values are later loaded in a 1-D Lookup Table block to for temperature, radiation, and wind data with time as breakpoint (see figure 9.2).

9.1.2. Convection

The convection heat transfer of the subsystem recieves ambient temperature, plate temperature, and wind speed as input parameters and give the convection heat transfer as output. The wind speed is used to give the convection coefficienct according to equation 8.5. The difference between plate temperature and ambient temperature forms a product with both the heat transfer coefficient and the total heat transfer area for solar thermal evaporator. The implementation can be viewed in figure 9.3.

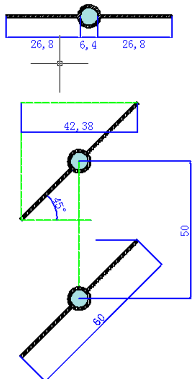

Figure 9.1.: Technical drawing of one finned tube collector. The collector has 16 finned tube in total and each is 2200 [mm] long.

9.1.3. Radiation Exchange

The radiation exchange between the plate and the surroundings recieves ambient temperature and plate temperature as input and radiation exchange as output. The ambient temperature is converted to the so-called sky temperature, T_{sky}, as described in in section 8.1, and, further, the radiation exchange calculated in accordance with equation 8.3. The implemetation can be viewed in figure 9.4.

9.1.4. Heat Pump

The heat pump subsystem receives plate temperature and condenser tempeature as inputs and gives compressor power, condenser effect, and evaporator effect as output. The subsystem consists of three subsystems; compressor, working enthalpies, and pressure ratio. The heat pump implementation can be viewed in figure 9.5.

The compressor subsystem receives evaporating and condenser temperatures as input. Evaporation temperature is used to detemine density at state 1, that being the inverse of v_1, of the refrigerant. Data for density is retrieved from a 1-D Lookup table with data from NREL refprop

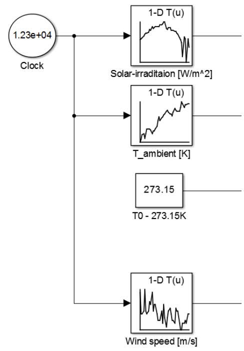

Figure 9.2.: Example of weather data implemented in a 1D-Look Up Table block.

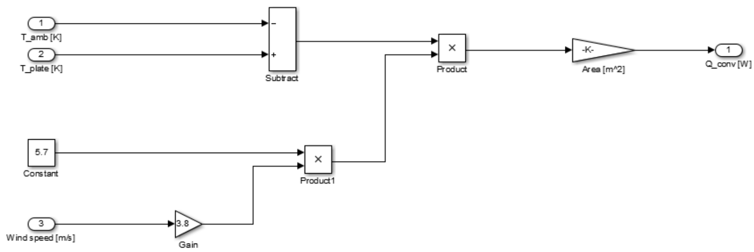

Figure 9.3.: Implentation of convection heat transfer in Simulink

database. Volumetric efficiency is determined in accordance with eq. 8.10. Finally, displacement, rotational speed, density, and volumetric efficiency are multiplied to determine the refrigerant flow rate. The implementation can be viewed in figure 9.6.

The working enthaplies subsystem receives evaporation temperature, condeser temperature and pressure ratio as input and use these two parameters to determine the working enthalpies of the heat pump. It is assumed a heat pump cycle where state 1, inlet of compressor, is located at vapour saturation line and state 3, outlet of condenser, is located at the at the liquid saturation line. Further, it is assumed an isentropic efficiency of the compressor determined by the pressure ratio over the compressor and an isenthalpic throttling process from the

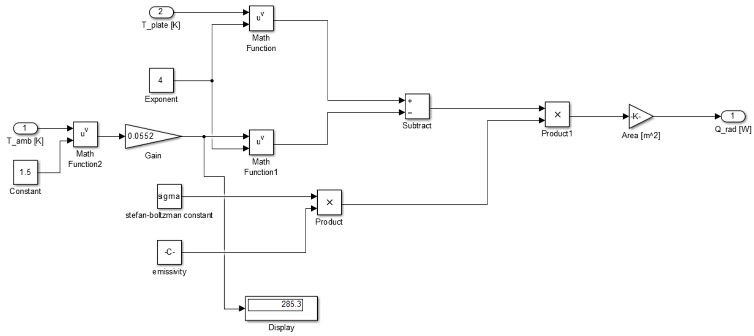

Figure 9.4.: Implementation of radiation exchange in Simulink.

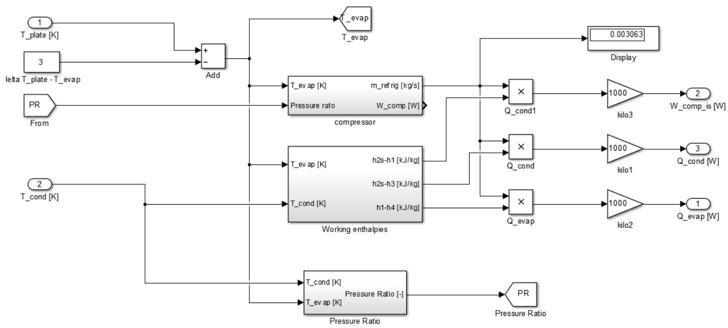

Figure 9.5.: Implementation of heat pump subsystem.

condenser to the evaporator. $h_1$and h_3 are obtained from 1-D Lookup tables and h_{2s}, an idealized compressor with no loss, is calculated by 2-D lookup table with pressure the condenser side and the entropy at state 1. After these operations the corresponding enthalpy differences for compressor, evaporator, and condenser are determined and given as output. The implementation of working enthalpies can be viewed in figure 9.7.

The pressure ratio are simply determined by 1-D Lookup tables using evaporation temperature and condesing temperature of the heat pump to determine saturation pressures. Further, the saturation pressure and evaporation pressure are divided to give the pressure ratio as output.

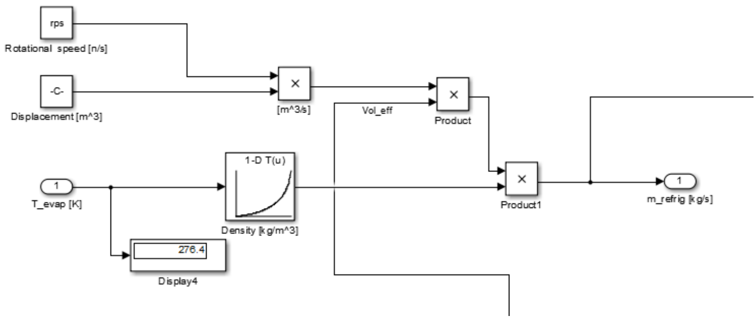

Figure 9.6.: Implementation of compressor in Simulink.

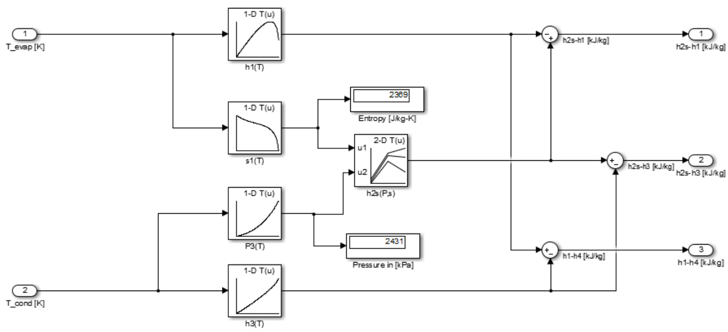

Figure 9.7.: Implementation of working enthalpies in Simulink.

The implemenation can be viewed in figure 9.8.

9.1.5. Water tank

The water tank model assumes that all heat rejected on the condeser is transferred to the water. Moreover, condenser temperature is assumed to be 10 degrees above the water temperature at any given time. The temperature differential of the water is detemined by the heat rejected divided by the thermal mass of the water, and this differential is then integrated to determine det water temperature. The water tank stops heating at 330 [K]. The implementation of the water tank can be viewed in figure 9.9.

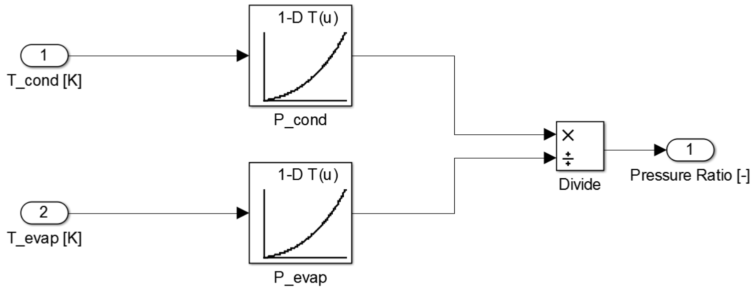

Figure 9.8.: Implementation of pressure ratio in Simulink.

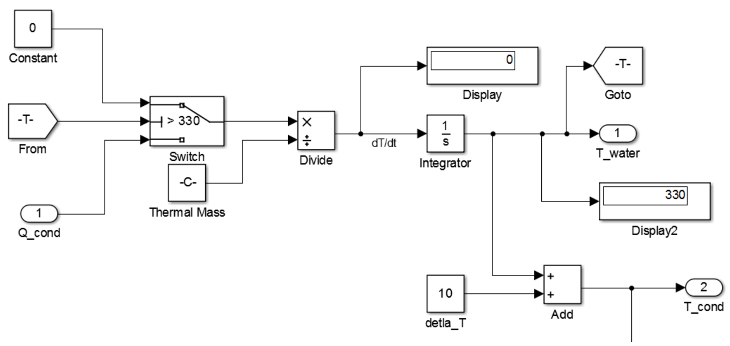

Figure 9.9.: Implementation of water tank in Simulink.

9.1.6. Energy dynamics

Energy dynamics of is implemented by adding and subtracking the energy flows in into the plate evaporator in accordance with equation 8.1. The thermal mass is divided and the temperature differential of the plate is the remaining output that is further handled by an integrator to give the plate temperature. The implementation of energy dynamics can be viewed in figure 9.10.

9.1.7. Model output

The model predicts the performance of the heat pump based on the solar radiation, ambient temperature and wind speed. Output values

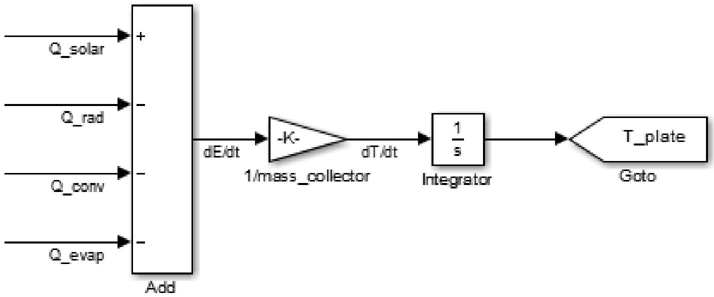

Figure 9.10.: Implementation of energy dynamics.

of different properties like COP, pressure ratio etc. are stored in a mat-files which are later used to make plots from the simulations (see figure 9.11).

9.2. Calculations of experimental data

The power consumption of the compressor is calculated by the trapz-function in MATLAB and the total energy transfer to the water was calculated by the temperature rise of the water mass. Total heat rejected divided by total power consumption determines the overall COP.

$$COP_{overall} = \frac{cp_{water} mass_{water} \Delta T_{water}}{\int W_{comp} dt} \tag{9.1}$$

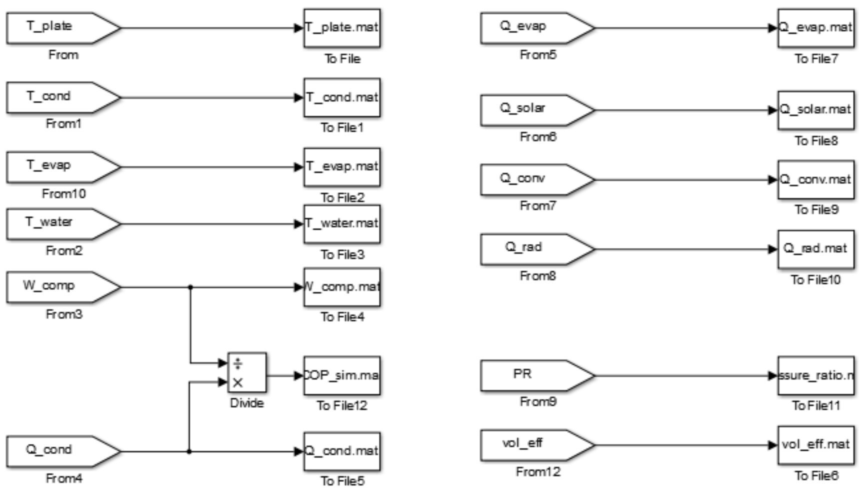

Figure 9.11.: Exporting output values from a simulation into mat-files.

10. Presentation of results

This section will present the results from both experiments and simulation of a the SAHP. The experiments were conducted using R22 and the simulation compares both R22 and R290. Experiments were conducted on a 150 liter water tank under overcast and sunny weather conditions and the simulation model uses these weather data as input.

10.1. Weather conditions during experiment

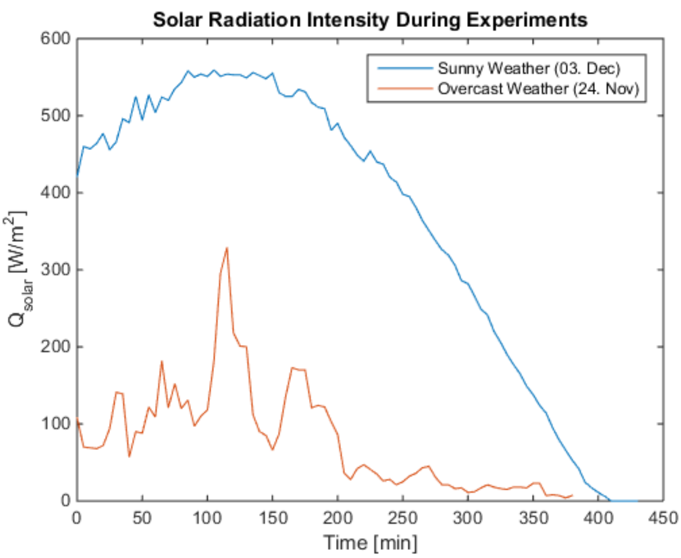

Figure 10.1.: Radiation conditions during experiments.

Experiments on an SAHP were conducted in overcast and sunny conditions on the 24th of November and 3rd of December, repectively.

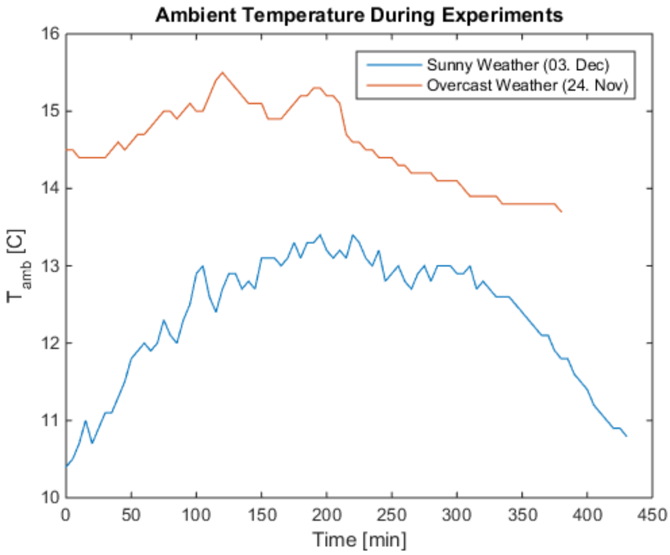

Figure 10.2.: Ambient temperature during experiments.

Mean weather conditions can be viewed in table 10.1.

Date:	Overcast 24.11.2015	Sunny 03.12.2015
Mean Temperature $[C]$	14.6	12.3
Mean Solar Radiation $[W/m^2]$	80	363.4
Mean ten-minute wind speed $[m/s]$	1.3	2.3

Table 10.1.: Mean weather conditions during days of experiments

The weather data was aquired from from the top of the GEL laboratory at SJTU which logs different weather data with 5 min intervals. Radiation data can be seen in figure 10.1, ambient temperatures data in figure 10.2, and wind speed data in 10.3.

10.2. Experimental results

In both experiments 150 liters of water was heated to a set point of 55 [C]. Experimental results can be viewed in table 10.2 Plots of the data logged during the experiments can be viewed in figure 10.4 and

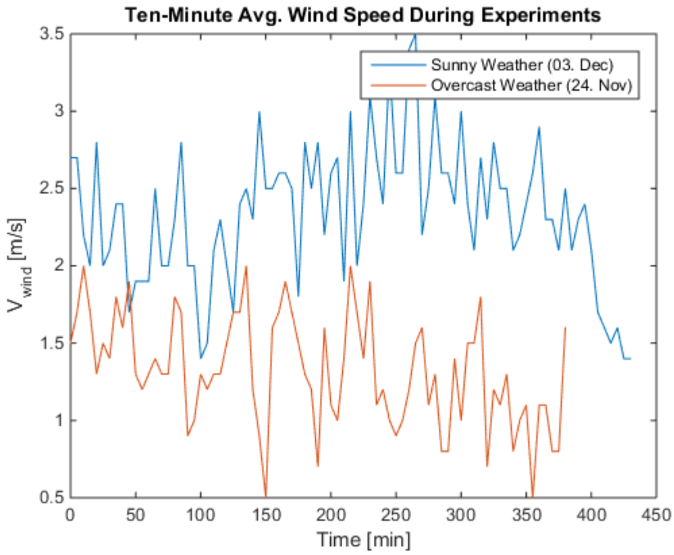

Figure 10.3.: Ten-minute average wind speed during experiments.

Date	Overcast 24.11.2015	Sunny 03.12.2015
T_{start}[C]	18	15
T_{end}[C]	55.5	55
Heating time [min]	381 (6 h 21 min)	428 (7 h 8 min)
Mean COP [-]	3.39	3.29
Mean Condenser effect [W]	1043.8	960
Mean Compressor power [W]	307.9	291.8

Table 10.2.: Results from experiments

figure 10.5 showing compressor power consumption and water tank temperature during experiments, respectively.

10.3. Simulation results

The compressor work from the simulations predicts a higher compressor work during sunny weather data compared to overcast weather data. This indicates that the convective heat transfer is very important for the heat pump model. Important simulation outputs can be viewed

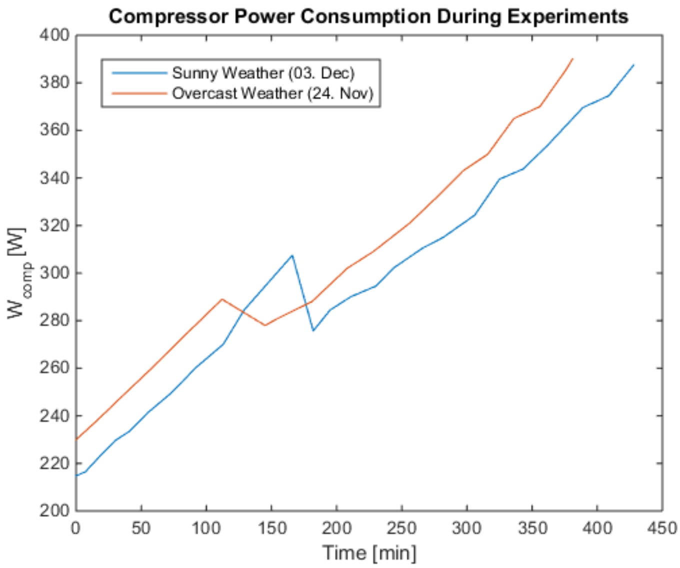

Figure 10.4.: Compressor power consumption during experiments.

in table 10.3, the outputs are calculated with the data series until the water temperature reaches its set point of 55 [C]. Figure 10.6 shows

Date	Overcast 24.11.2015	Sunny 03.12.2015
R22 Mean COP [-]	7.38	7.95
R22 Mean Condenser Effect [W]	1269	1508
R22 Mean Compressor Work [W]	167	189
R22 Heating Time [min]	320 (5 h 20 min)	286 (4 h 46 min)
R290 Mean COP [-]	4.90	8.11
R290 Mean Condenser Effect [W]	1508	1092
R290 Mean Compressor Work [W]	236	192
R290 Heating Time [min]	380 (6 h 20 min)	343 (5 h 43 min)

Table 10.3.: Key output parameters from simulation model.

compressor work for R290 and R22 with sunny and overcast weather data, respectively.

Plots of the simulated condenser effect can be viewed in figure 10.7. The simulation model predicts a significantly lower pressure ratio for

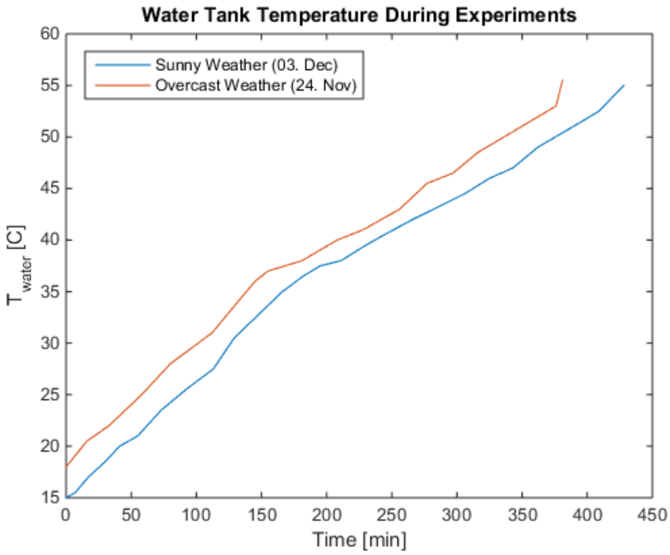

Figure 10.5.: Water temperature during experiments.

R290 compared to R22. The results is also expected due to the thermophysical properties of R290. Plots of the simulation results for pressure ratio can be viewed in figure 10.8. Figure 10.9 shows the predicted COP plots from simulations. The plate temperature is predicted to be slightly higher for R290 and plots of the simulation results can be viewed in figure 10.10. The simulation model predicts that R22 will heat the water in the water tank faster than R290 and the simulation plots can be viewed in figure 10.11. The volumetric efficiency is on average the same for R22 and R290 in simulations and figure 10.12 shows the predicted volumetric efficeincy from the simulation model. The simulation model predicts mass flow rate of R290 is 49% compared to R22 in simulations, which is to be expected due to the thermophysical properties of R290. Plots of the predicted refrigerant flow can be viewed in figure 10.13.

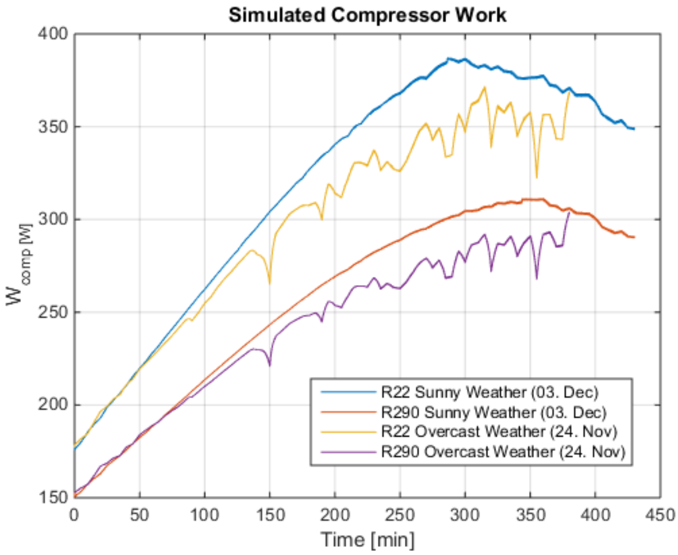

Figure 10.6.: Predicted compressor work from simulations for both R290 and R22.

10.4. Comparison between simulations and experiments

The simulation results predicts a higher efficiency of the heat pump system than the experiments, and further a higher effects in both condenser and evaporator. The simulation model is closely linked to a weather data input and simulation results is hence closely correlated with the solar radiation. The experimental results are less fluctuating than the simulation model.

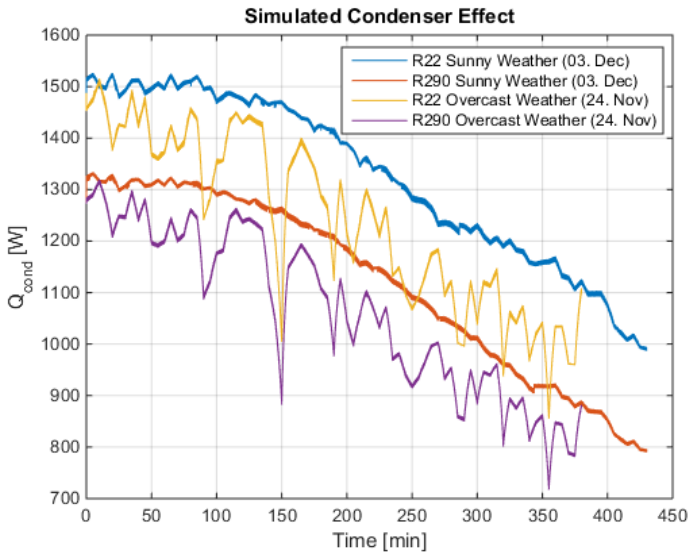

Figure 10.7.: Predicted condenser effect for both R290 and R22.

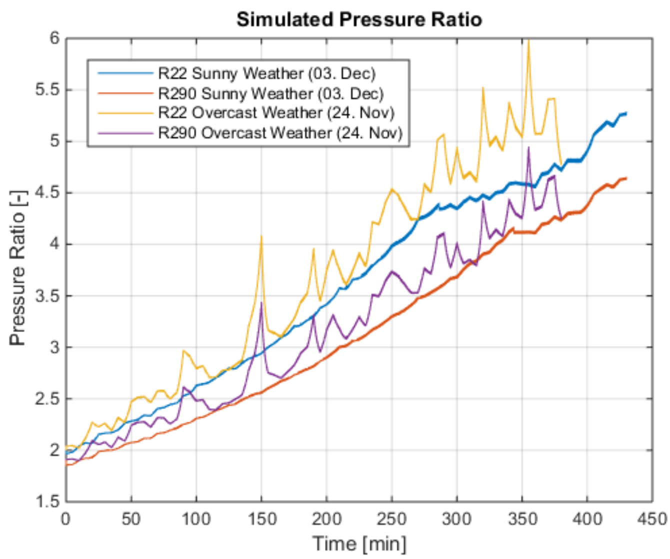

Figure 10.8.: Predicted pressure ratio for both R290 and R22.

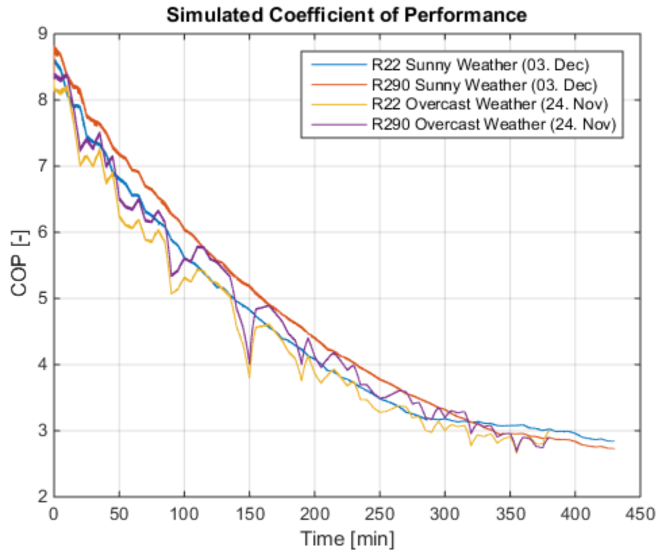

Figure 10.9.: Predicted COP for both R290 and R22.

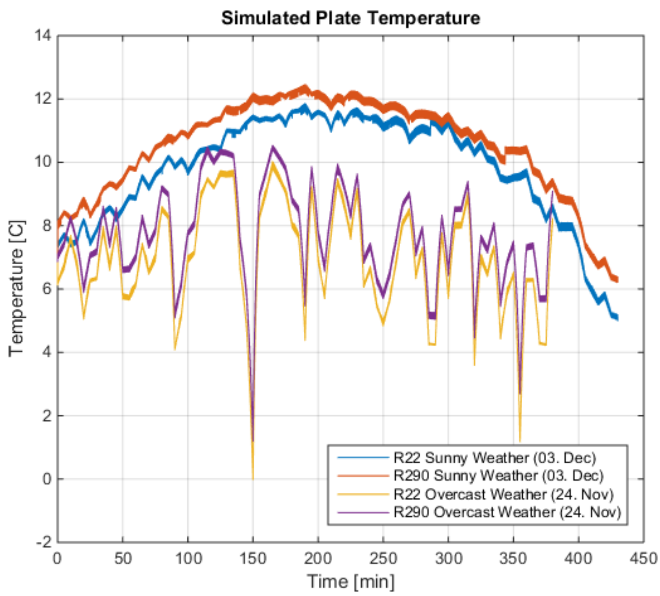

Figure 10.10.: Predicted plate temperature for both R290 and R22.

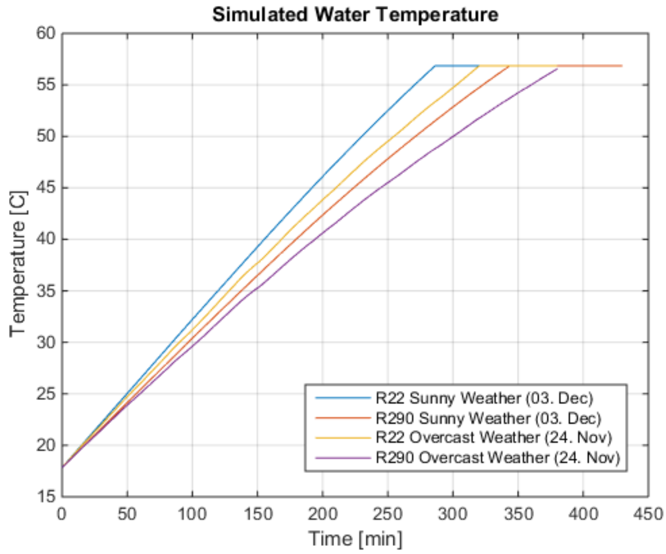

Figure 10.11.: Predeicted hot water temperature for both R290 and R22.

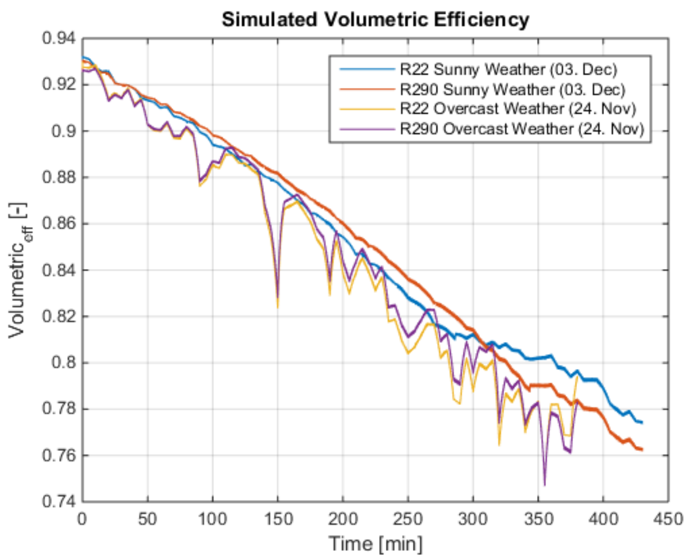

Figure 10.12.: Predicted volumetric efficiency for both R290 and R22.

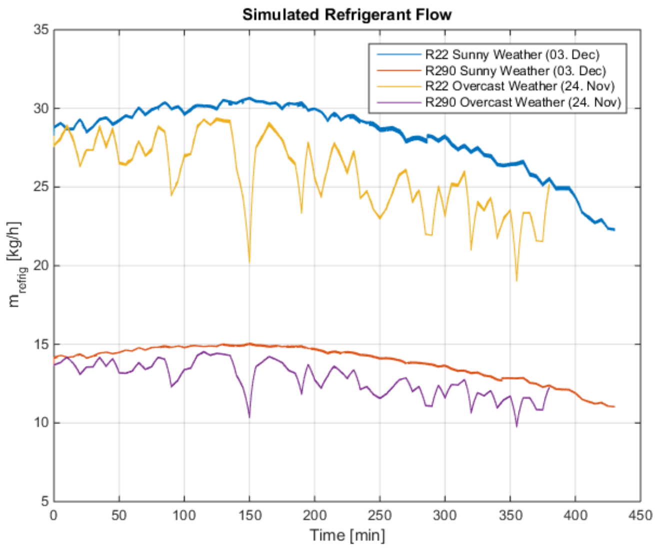

Figure 10.13.: Predicted refrigerant flow for both R290 and R22.

11. Discussions

This discussion section will highlight some improvements that should be done regards to simulation model and further some thoughts on how SAHPs can be incorporated in a beneficial way.

11.1. Suggested improvements of experiments

The solar-collector evaporator is the most important feature of a DX-SAHP and investigations into effective solar-collector design is needed. A proper test-rig where new solar-collector evaporator designs, different compressors, expansions valves and other components easily could be changed would greatly facilitate the speed of experiments and results. A test rig should have all neccessary measurement built-in as pressure sensors, temperature sensors, flow meters etc and be automatically logged to a computer software. Key components should be easy to change so that a range of experiments can be conducted in a short time comparing different components and refrigerants.

11.2. Suggested improvements in simulations

Building a simulation model from "scratch" is great learning but the results have a great chance of not being realistic or a greater possibility for failure. I would suggest to develop a some kind of framework for SAHPs in modeling softwares like Dymola, TRNSYS, or more detailed CFD solutions in softwares as Fluent. A team should develop this together and document the process and validate the models with experiments.

11.3. From a technical and theoretical possibility to a commercial success

A key point to be highlighted in this thesis is that SAHPs have an advantages under certain conditions and that it will inevitably going to compete with other heating technologies. From a consumer point of view, investment cost and the fact that hot water will be available when they need it is of prime imporatance. If consumers want hot water in the morning heat produced the day before must be availible next morning, preferably, to avoid night time operation. Installation personel will judge SAHPs by their abillity to be easily and fast to install. From an environmental point of view, SAHPs ability to generate energy savings will be the crucial factor. This fact argues for different actions at different levels and, most importantly, to ensure that SAHPs are installed where they have a high probability to give energy savings compared to other techonologies. In practical terms, this means that SAHPs need to be built for different conditions, e.g. we can envision different SAHP models for different levels of solar irradiation. Futher, SAHPs should be designed to meet the heating demand when it is needed the most. However, this might also call for a need for backup heating solutions like natural gas or electric heating. Practical implementation might suggest that a SAHP will meet the full heating demand in 10 out of 12 months and partially meating the demands in 2 winter months with a backup heating from electricity or gas to handle peak heating loads. The point here is to put forward a specified roadmap for SAHPs expicitly stating how SAHPs can out-perform other heating technologies in a variety of parameters and truly define its place as a heating technology.

Many authors suggests variable speed compressors to be implemented with SAHPs so the evaporator effect can be closely matched with the incomming solar radiation. For small kit system of SAHPs a two-stage regulation of compressor speed might be all that is needed to ensure a proper regulation and an elevated evaporation temperature.

Water tank design. Ensuring the possibility of hot water is also important. This might argue for a water-tank design that is a different. One can envision a tank where 50 liters is garuanteed to be heated and 100 additional liters that are heated in times of solar radiation. Hot water tanks also have to be ensure safety in terms of growth of bacteria as salmonella.

11.4. Suggestions on how to organize a work group

A basic team should be devoted to research on Solar-Assisted Heat Pumps at SJTU and have online document base where what work that has been done is availible and who has done it. This is especially important when dealing working internationally as language and cultural barries can be of hindrance of progress. Having a clear idea of status and direction in research is therefore even more important.

The more easy it is to start understanding, developing, and learning a new technology the greater the chance is for success. By having a team working on these problems consistently over time focusing on specific tasks, it can more easily be carried out and pace of development can improve.

12. Conclusions

Experiments were conducted on a SAHP with R22 as refrigerant with in overcast and sunny weather conditions with and average COP of 3.39 and 3.29, respectively.

A simulation model was developed to compare R22 and R290 as refrigerant. The simulation model used experimental weather data as input and predicted an COP of 4.68 for R290 and 4.47 for R22. The simulation model predicted a refrigerant flow of 49% less for R290 compared to R22. The simulation model is not validated by any experiment.

In the discussion section it is suggested to build a test rig for SAHP where key components can easily be changed and experiments rapidly conducted. The process of research on SAHPs should be documented and follow a clear stated strategy. The approach of research should be more team-based, meaning that we students work in structured manner to solve research problems concering SAHP. SAHPs should further be developed with natural refrigerants as the world as a whole is trying to move away from environmental hamfull artificial refrigerants.

13. Proposals for further work

Based on findings, investigations, and conclusions in this report following tasks should be concidered regarding SAHPs.

- Develop a sealed Solar-Assisted Heat Pump using R290 as working fluid in compliance with EN378 regulations. Note that max. charge of R290 is dependant on room size but should not be a problem it the water heater is situated on a balcony.
- Make a test rig which can easily perform measurement on different collector-evaporator designs and compressors.
- Investigate different collector-evaporator designs, like designs with a concentrators to further elevate the evaporation temperature during periods of direct solar irradiation.
- Develop different SAHPs for different climate conditions based on mean radiation and mean temperature in heating season. Example of design parameters can be ambient temperature of 10 [C] and mean radiation 500 $[W/m^2]$.
- Different SAHPs for different customers. A residential customers have different needs than that of a hotel hotel customer. Easily installable SAHP kits should be developed residential customers.
- Have clear design criteria, eg. that the solar assisted heat pump only will work when elevated temperatures can be achieved. If the same location is using PV-panels, PV output can be used

as an indicator when to start the SAHP. Develop digital portal where people can estimate their potential for solar energy like PVWatts Calculator[1] in the US.

- Develop a specific roadmap with concrete tasks for the development of SAHP. Have clear projects where specific tasks are handled and work on them in teams. Have “task force” which will work on different issues concering a SAHP and can easily integrate new team members. This is especially important when including people of different nationality.

[1]visit pvwatts.nrel.gov/index.php

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A. MATLAB Scripts

A.1. Initialisation script

```
%Loading scripts

load('wind03dec.mat')    % wind data from 03 december
load('rad03dec.mat')     % radiation data from 03 december
load('temp03dec.mat')    % temperature data from 03 december
load('time03dec.mat')    % time data from 03 december

load('wind24nov.mat')    % wind data from 24 november
load('rad24nov.mat')     % radiation data from 24 november
load('temp24nov.mat')    % temperature data from 24 november
load('time24nov.mat')    % time data from 24 november

load('ex24nov.mat')      % experimental data from 24 November
load('ex03dec.mat')      % experimental data from 03 December

propertygenerator        % script for generating refrigerant properties

%Parameters for Solar Assisted Heat Pump

absorbtivity = 0.94;     % absorbtivity [-]
area_solar = 2.2*.8;    % collector area [m^2]
area_convection = 2.2*2*(16*.06);    %area for convection [m^2]
cp_plate = 0.9020;       % specific heat aluminum/collector [kJ/kg-K]
emissivity = 0.2;        % emissivity for collector
mass_plate = 9;          % mass of evaporator material in [kg]
sigma = 5.67e-8;         % stefan-boltzmann constant
thermal_mass = 630000;   % thermal mass of 150 liter water [kJ/K]
rps  = 2860/60;          % revolutions per second for the compressor
displacement = 7.4e-6;   % cylinder displacement in m^3
phi_0 = 0.15;            % displacement fraction for compressor
area_tube = 16*2*(0.0032.^2*pi); %internal area tube evaporator
```

A.2. Property generator

```
% - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
% This script makes termodynamic relations for a heat pump cycle from the
% NIST Refprop database.
%
% State point one, inlet compressor, and state point 3, outlet
% condenser, are assumed to be at the saturation line of vapour and liquid,
% respectively, of the refrigerant chosen. State point 2 can be obtained by
% knowing the entropy of state point 1 and pressure of state point 3. The
% throttling process from state 3 to state 4 is assumed to be isenthalpic.
%
% The data generated here is further used in a simulink model of a
% solar-assisted heat pump.
% - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

% Parameter range for properties.

P_upper = 5000; % upper pressure in kPa
P_lower = 200;  % lower pressure in kPa
P_delta = 50;   % pressure increment in kPa

T_upper = 369;  % upper temperature in K
T_lower = 250;  % lower temperature in K
T_delta = 1;    % temperature increment in K

S_upper = 2000; % upper entropy in J/kg-K
S_lower = 1500; % lower entropy in J/kg-K
S_delta = 10;   % entropy increment in j/kg-K

%Refrig = 'R22';
Refrig = 'propane';

i = 1;          % matrix index

%Initilizing matrixes

h_gas = zeros((S_upper-S_lower)/S_delta,(P_upper-P_lower)/P_delta);
h_satliq = zeros((T_upper-T_lower)/T_delta,1);
h_satgas = zeros((T_upper-T_lower)/T_delta,1);
s_satgas = zeros((T_upper-T_lower)/T_delta,1);
P_satliq = zeros((T_upper-T_lower)/T_delta,1);
D_satgas = zeros((T_upper-T_lower)/T_delta,1);

Temperature = T_lower:T_delta:T_upper;
Pressure = P_lower:P_delta:P_upper;
Entropy = S_lower:S_delta:S_upper;

```

```
for T=T_lower:T_delta:T_upper
    h_satliq(i,1) = refpropm('H','T',T,'Q',0,Refrig);
    h_satgas(i,1) = refpropm('H','T',T,'Q',1,Refrig);
    s_satgas(i,1) = refpropm('S','T',T,'Q',1,Refrig);
    P_satliq(i,1) = refpropm('P','T',T,'Q',0,Refrig);
    D_satgas(i,1) = refpropm('D','T',T,'Q',1,Refrig);
    i = i+1;
end

i = 1;  %matrix index
j = 1;  %matrix index

for S =S_lower:S_delta:S_upper
    for P=P_lower:P_delta:P_upper
        h_gas(i,j) = refpropm('H','P',P,'S',S,Refrig);
        j = j+1;
    end
    i = i+1;
    j = 1;
end

% finalization of data.
h_gas = h_gas/1000;          % enthaply in kJ/kg
h_satliq = h_satliq/1000;    % enthaply in kJ/kg
h_satgas = h_satgas/1000;    % enthaply in kJ/kg

%K = cp/cv

K = refpropm('K','T',300,'P', 2000, Refrig);    %retriveing the cp/cv ratio
```