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Seven PhD Studies on Solar District Heat

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Abstract

The Solar Heat Integration NEtwork (SHINE) is a European research school in which 13 PhD students in solar thermal technologies are funded by the EU Marie-Curie program. It has five PhD course modules as well as workshops and seminars dedicated to PhD students both within the project as well as outside of it. The SHINE research activities focus on large solar heating systems and new applications: on district heating, industrial processes and new storage systems. The scope of this paper is on systems for district heating for which there are six PhD students, three at universities and two at companies. In addition there is a seventh PhD in a Swedish national research school focused on energy efficiency within district heating networks (Reesbe). The initial work has concentrated on literature studies and on setting up initial models and measurement setups to be used for validation purposes. Some results of these studies are presented in the paper. The PhD students will complete their studies in 2017-18.

Keywords: solar thermal, district heat, research school

1. Introduction

Since 2006 there has been a European collaboration on graduate education within the field of solar thermal, SolNET (Jordan et al., 2007). The initial four years was funded mainly by the EU Marie-Curie program but also by national funding in the different participating countries. Seven courses for PhD students were taught and 10 PhD students were trained in this initial project. The network was so successful that the collaboration continued after the end of the first project with one PhD course planned per year. The first PhD projects funded within SolNET focused mostly on small scale systems. A new project funded by the EU Marie-Curie program, Solar Heat Integration NEtwork (SHINE), started at the end of 2013 and is focused on large scale systems and thermal storage. In total 13 PhD students are funded in this project, of which six have projects that are related to solar district heat. Five Ph.D. courses will be organized by the participating universities.

The work is split into three different work packages: WP1, focusing on solar district heating (and the subject of this paper); WP2, studying solar heat for industrial processes; and WP3, focusing on sorption processes and materials. The overall research objectives within these three fields are:

- to reduce the large planning efforts (requiring expert knowledge) for systems integration into existing heating systems for new applications, especially for industrial processes,
- to optimize complex hydraulics in terms of flexibility to serve variable loads, overall collector efficiency, pressure drop and safety of collector stagnation for different boundary condition, to optimize operation strategies of the respective solar heating systems,
- to provide large, but inexpensive components like large stores and collectors,
- to detect errors within the complex hydraulics and controlling and to suggest suitable maintenance activities,

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- to identify barriers within the supply chain and in the decision processes of the potential purchaser that limit the large scale implementation of the technology, and to improve the performance of sorption materials via chemical modification and combination of fluid solid hybrid materials.

Figure 1 shows a map with the participating organisations within SHINE and the preliminary title of their PhD study.

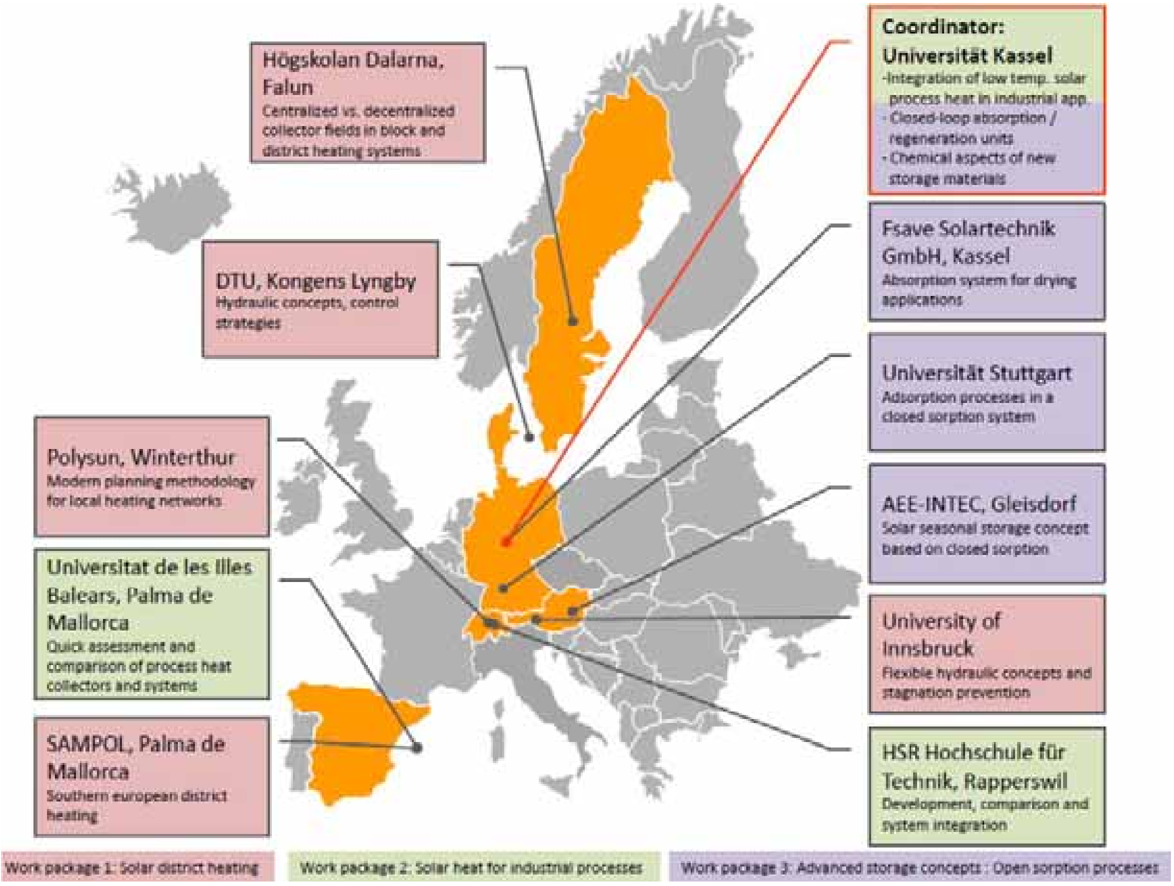


Fig. 1: Participating organizations and their PhD projects within the SHINE project showing the split into the three different focus areas (work packages)

The Swedish national research school, Reesbe, also started in 2013 with 12 "industrial" PhD students, where the students work half of the time in the university and half at company. Reesbe focusses on energy efficiency measures within the built environment encompassed by district heating grids, and most companies involved are either housing companies or district heating utilities. One PhD student, studying feed-in solar district heating systems, is working for a consulting company and is collaborating with the SHINE PhD students.

The aim of this paper is to present the seven projects related to solar district heating in these two research schools and the first results from them.

2. The PhD projects and their first results

In this chapter the main aims of each PhD project is described together with some results from the first studies.

2.1. Techno-economic analysis of centralised and decentralised solar district heating plants

The PhD project at Högskolan Dalarna (SERC) will be made by Christian Nielsen, supervised by Chris Bales at Högskolan Dalarna and Jan-Olof Dalenbäck at Chalmers University of Technology. The main aims are to analyze the advantages and disadvantages of centralized and decentralized solar collector fields in district heating networks and to derive the technological and economic boundary conditions for profitable operation. Both de-centralized feed-in (connection on primary side) and district heat augmented systems (connection on secondary side) will be covered. Systems in operation will be closely monitored and analyzed for comparison.

An analysis of the solar collector system on the façade of Högskolan Dalarna in Borlänge, Sweden, is ongoing. Heating for the building is mainly supplied by district heat, while the solar heating system is connected on the secondary side. The solar heat is currently used for heating the hot water circulation loop of the building, covering the circulation heat losses when possible. The flat-plate solar collector area is 73 m^2 and the total hot water storage volume is 4.5 m^3. Based on yearly energy measurements it was realised that the system is not optimally utilizing the available solar energy, due to the hydraulic setup (Izotov, 2011). Thus the system was modelled and simulated in TrnSys to estimate the energetic benefits of making some minor system and control modifications. Simply moving a mixing valve from the cold water (CW) inlet to the domestic hot water circulation (DHWC) will enable solar pre-heating of the cold water supply for domestic hot water, besides covering part of the circulation heat losses (see fig. 2).

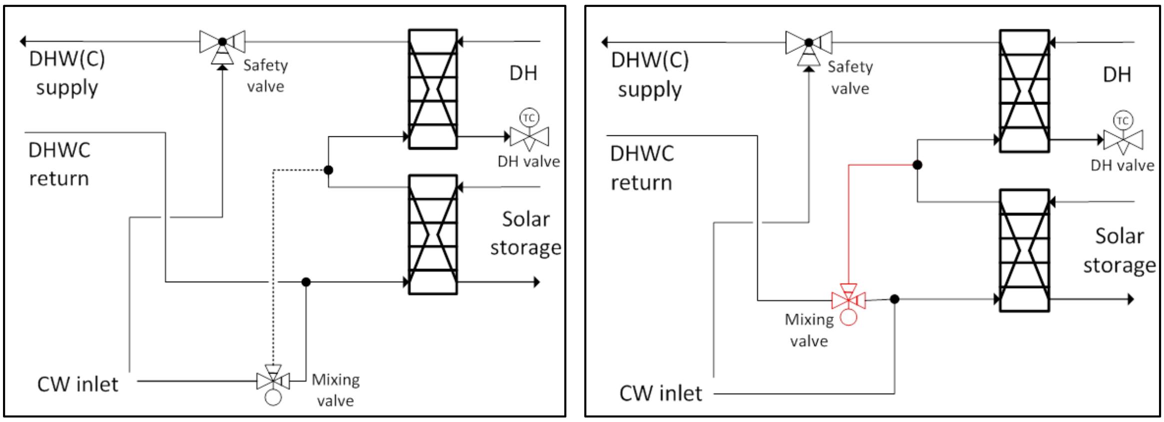


Fig. 2: Current (left) and future (right) setup of cold water and recirculation water mixing

The simulations showed that this solution significantly increases the number of hours where solar heat is utilized, and consequently also the collected solar energy and the net utilized solar energy (NUSE) (i.e. solar energy delivered from storage). The total yearly energy demand for hot water consumption and circulation losses is around 79 MWh. As seen in tab. 1 it is expected that the solar energy collected will increase from 41 to 44 MWh per year. The utilized solar energy increases from 26 to almost 35 MWh, out of which more than half (19 MWh) of the energy will be used for cold water pre-heating in the new setup, since much lower temperatures are needed for this purpose. Thus this simple modification will save a significant amount of district heat (and thereby money) during the lifetime of the system.

Tab. 1: Yearly results for the current system and the future solution modelled with TrnSys

	Total energy demand [MWh]	Solar energy collected [MWh]	Net utilized solar energy [MWh]	NUSE to cover circulation losses [MWh]	NUSE to CW pre-heating [MWh]
Current system	77.9	40.5	26.4	26.4	0
Future solution	78.0	44.2	34.7	15.6	19.1

Another system being analyzed is a solar-assisted block heating system in Vallda Heberg outside Gothenburg, Sweden. The network consists of low-energy houses and apartments in a new residential area, where space heating and domestic hot water are supplied via a novel heat distribution system. System data for the first year of operation shows that both the system heat demands and collected solar energy are similar to the expectations (Nielsen, Haegermark and Dalenbäck, 2014). The system will also be modelled, and used in comparative studies of different types of solar-assisted district heating networks.

2.2. Southern European District Heating

The PhD project at Sampol Ingenieria y Obras S.A. will be carried out by Nicolás Pérez de la Mora, supervised by Vincent Canals and Victor Martinez Moll at Universitat de les Illes Balears. The PhD focuses on demand and electricity price forecasting. The developed forecast tools will be included in a set of appropriated computer tools which will work together with thermal simulation software TRNSYS in order to estimate the energy generation strategies by determining the energy production mix that minimizes the energy cost and optimize the electricity production. This will lead to an optimization of the plant operation and integration of the solar field.

The first efforts have focused on the modeling of the existing “Parc Bit” plant in TRNSYS and the energy price forecasting tool. Parc Bit is a power plant comprising a CHP (Combined Heat and Power) plant with a biomass boiler and solar collectors support. In order to maximize the plant’s revenue for energy generation generation and demand curves need to be matched. To achieve good operation an accurate estimation (forecast) of thermal energy consumption and the electricity spot market price is required. The idea is to use the generated forecasts in a plant model to help the plant‘s manager to improve the generation strategies and to reduce expenses and maximize revenues.

A two core electricity forecasting tool was developed based on SARIMAX (Seasonal Auto Regressive Moving Average with Explanatory variables) and ANN (Artificial Neural Networks) methods in order to obtain the future energy price. Fig. 3 shows the distribution of the error calculated as difference between the real price and the forecasted for both methods.

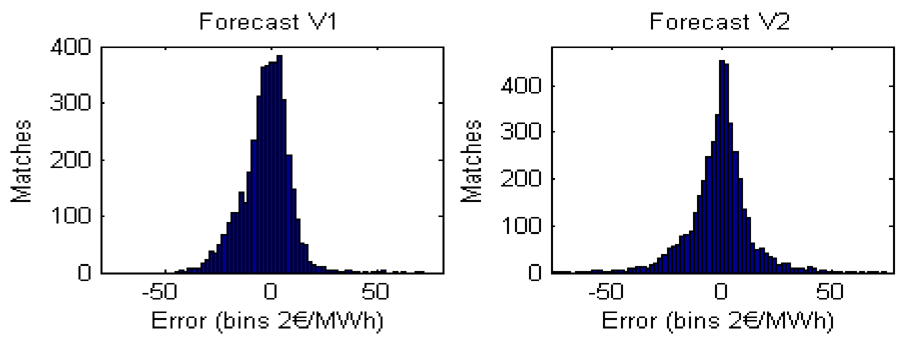


Fig. 3: Errors for SARIMAX and ANN models

In order to decide which technology will supply the load, the hourly electricity price is forecast and the thermal load supply cost was estimated for the different technologies in the power plant. The generation strategy is chosen so that revenues are maximized.

As a test, the operation minimum [€/MWhele] to start up the CHP plant was varied to calculate the significant error of the tool in different scenarios. The electricity price is forecasted; therefore, this value becomes critical when deciding whether or not the CHP shall be turned ON or OFF. After studying the decisions brought from the forecasted values, four possibilities are found: Generation leads to benefits; No-generation leads to no- costs; Generation leads to costs; No-generation leads to no-benefits. The sum of the occurrences for the first two possibilities gives the success rate, while the sum of the last two the failure rate. Tab. 2 shows the results of the test using the SARIMAX model for the period 1/1/2014 to 1/7/2014. The success rate is roughly the same high value (~85%) for all CHP operation minimum price, showing the model performs well enough over a large range of conditions.

Tab. 2: Results of success/fail of forecasts

CHP Operation minimum price	Generation & Benefits	No-Generation & No-Costs	Generation & Costs	No-Generation & No-Benefits	Success	Fail
20 €/MWhele	70.7%	12.6%	13.9%	2.8%	83.3%	16.7%
25 €/MWhele	64.5%	20.0%	11.5%	4.0%	84.5%	15.5%
30 €/MWhele	55.4%	29.6%	9.5%	5.5%	85.0%	15.0%
35 €/MWhele	45.8%	39.9%	7.6%	6.7%	85.7%	14.3%
40 €/MWhele	33.6%	51.2%	6.8%	8.4%	84.8%	15.2%

2.3. Modern Planning Methodology for Local Heating Networks

The PhD project at the software company Vela Solaris AG is pursued by Artem Sotnikov and supervised by Andreas Witzig at Vela Solaris and Wolfgang Streicher at the University of Innsbruck. The main aims are to develop and validate a powerful and user-friendly tool which supports the planning of solar district heating networks based on the well-known tool Polysun.

The methodology of the study has been defined. New models are to be developed in Java programming language, which allows applications to have fast computing time as well as being flexible for possible changes and extensions. Developed models will be validated against measurement data from real systems obtained through the SHINE and Vela Solaris AG networks and with TRNSYS simulation software.

The first task is the extension of Polysun`s building model to cover multiple residential units within one system boundary (see Fig. 4). This goal requires also the extension to models of heating elements and system components which are subject of heat interaction with building (e.g. storage tank).

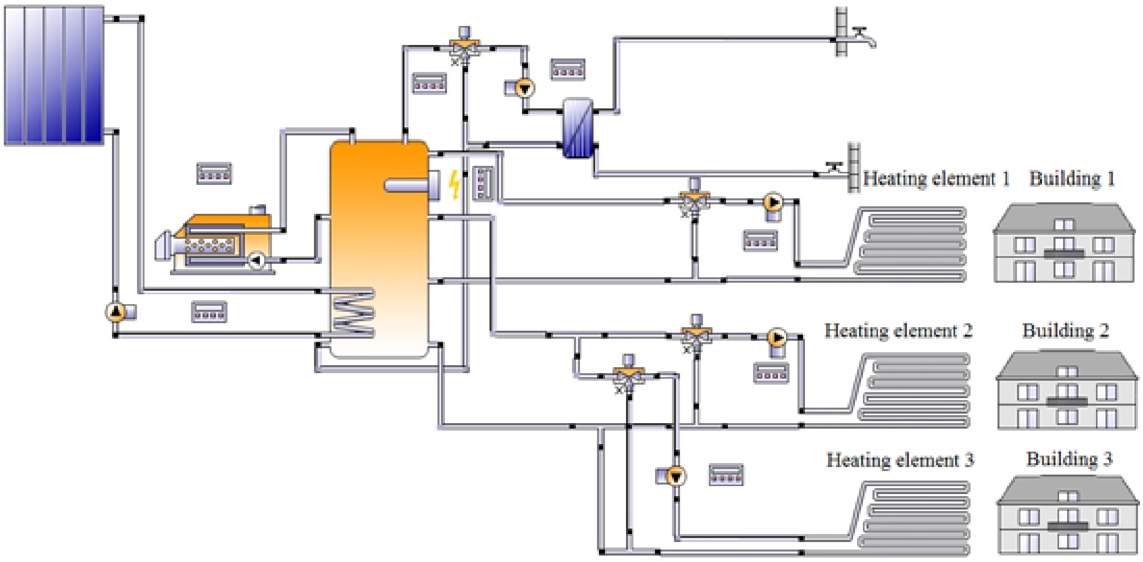


Fig. 4: Layout of multiple residential unit system in Polysun simulation software. A typical simulation study is to evaluate system performance for district heating, taking into account distribution losses and comparing different system topologies.

The first results have been obtained. The building model and the heating element model have been extended for given case. System simulation with unlimited number of buildings within its boundaries is possible. Tab. 3 shows simulation results for the reference case (see Fig. 4). Results prove that each building is simulated independently from each other.

Tab. 3: Simulation results (energy from heating modules to building units and storage tank losses in kWh on monthly basis). B – building, TL – storage tank losses. Results for heated area B1=150 m², B2=200m², B3=250m² (all buildings with German 2010 insulation standards).

Name	Jan.	Feb.	Mar.	Apr.	Mai	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Year
B1	960	630	160	0	0	0	0	0	0	0	590	980	3320
B2	1160	730	100	0	0	0	0	0	0	0	630	1200	3820
B3	1710	1190	410	0	0	0	0	0	0	0	1170	1740	6220
TL	210	200	220	180	180	170	170	180	180	190	200	200	2280

The next step is extension of the model for heat losses model in order to cover all system components which have heat interaction with a building unit. After that each extended model as well as their joint performance will be validated against measurement data. Also TRNSYS simulations will be conducted for the same boundary conditions in order to validate developed models against TRNSYS results.

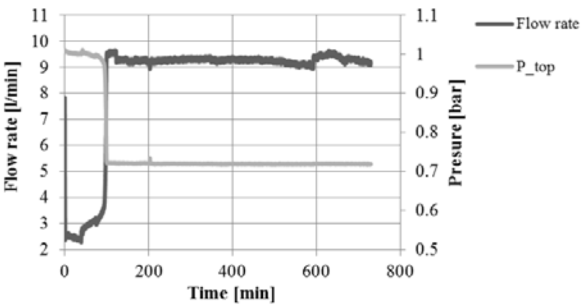
2.4. Design, investigation and modelling of innovative solar drainback systems

The PhD project at the company FSAVE Solartechnik GmbH will be carried out by Yoann Louvet, supervised by Katrin Zass at the company and Klaus Vajen at the University of Kassel. The main purposes are to investigate so called drainback systems (DBS) and to acquire better knowledge on this technology, which is potentially interesting for the future of solar thermal systems (Perers, 2006; Furbo et al., 2012). The focus will be on understanding the mechanisms and special issues at stake with DBS, especially in the context of large systems, and proposing improvements for their design.

Resorting to the drainback concept in the solar thermal field has already been known for a long time; however DBS represent the majority of the solar installations only in a few countries, namely the Netherlands, Norway and Belgium (Botpaev and Vajen, 2014). DBS especially provide an adequate overheating and freezing protection, reducing the needs for maintenance. However inappropriate design or simple installation mistakes can be severely damageable for DBS. A better understanding of their functioning is therefore necessary to facilitate the spreading of this technology.

In a first step, a review of existing literature and scientific materials related to DBS will be carried out to synthetize the current state of the research on the topic. So far, the search for literature has been completed, and the results are being compiled to provide a comprehensive overview of DBS. The extensive research nonetheless revealed that available literature is very limited and most of it dates back a few decades.

Along with this theoretical part, the investigation of existing large commercial DBS (with a surface of collectors larger than 100 m²) is planned, to gather experience on the specific behaviour of DBS. To do so, appropriate sensors and data logging equipment have been installed for monitoring. Two plants are already being examined. In addition to those field tests, experiments have been carried out with a previously built test rig (without actual solar collector) revealing some specificities of DBS. Fig. 5a, depicts the creation of a siphon during the filling phase of the DBS in the flow pipe. This siphon is fundamental as it decreases the energy consumption of the pump(s) during operation. With an unpressurized system, the creation of this siphon can be easily identified, as shown in the figure, as it leads to an under-pressure at the top of the system. The flow rate increases drastically as a consequence, highlighting the fact that the pump does not have to overcome the static head anymore. For a “proper” operation of the DBS, the siphon needs to be built within a few minutes after the start of the pump(s). Nevertheless when the flow rate is situated below a certain range, as it is the case in Fig. 5a and b, the formation of the siphon and therefore reaching the proper operation mode can last more than an hour, which is obviously not desired. Fig. 5b, shows that the filling phase carried out under identical conditions is not repeatable, suggesting that a correlation between filling time and filling velocity might be difficult to obtain. From those experiments, one can however advise to fill DBS at a high velocity, to avoid a lengthy filling process. Further experiments will come to clarify this point.



Experiment	Filling time
First	1 hour 05 minutes
Second	1 hour 39 minutes
Third	> 3 hours

Fig. 5: a) The flow rate in the return side and the pressure at the highest point of the hydraulics show the typical appearance of a siphon in the DBS at the end of the filling phase (left); b) At low flow velocities, the filling phase might last a while. Repeating the identical experiment three times does not reveal any correlation between filling velocity and filling time (right)

In order to further analyse DBS, a test facility with an actual solar collector, making it possible to vary operational parameters and to test various components as well as the proper “drainback” capability of the installation (filling, draining…) has been designed and is under construction.

2.5 Solar collector fields for solar heating plants in district heating systems

The market for solar heating plants connected to district heating systems is expanding rapidly in Denmark. It is expected that the strong growth in this field in Denmark will continue in the coming years (Furbo et al., 2014). In such a scenario, even a small efficiency improvement may lead to a large increase in the overall energy production in absolute terms. For this reason, the PhD project at the Technical University of Denmark (DTU) will focus on the development of detailed TNRSYS simulation models for solar collector fields, in order to investigate and optimize the design of the solar collector field, the control strategy and the flow distribution within the field. The shadow effect from one row to another, heat losses from the supply pipes, heat capacity of the collectors and pipes, influence of flow rate and tilt angle on the collector efficiency will also be considered. This project will be carried out by Federico Bava, under the supervision of Simon Furbo and Jianhua Fan, and in cooperation with the Danish company ARCON Solar A/S, one of the major suppliers of large scale solar collector fields.

In its initial phase the project has developed an Excel model which can calculate the pressure drop over large solar collectors. The model is a first step to study the flow distribution in the entire solar collector field. The model was validated against experimental results with different operating conditions of flow rate, temperature and fluid type (Fig. 6).

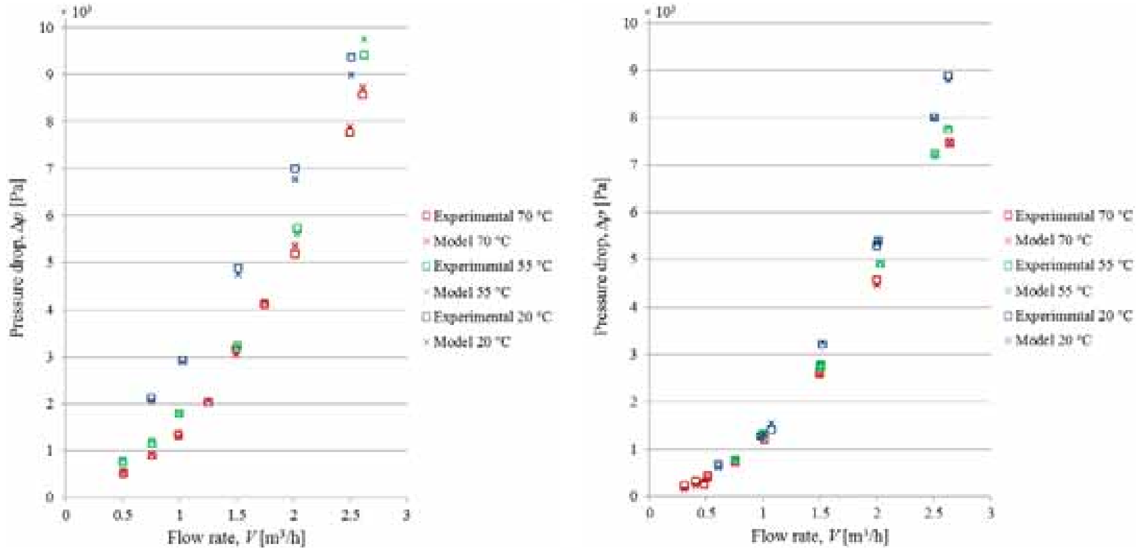


Fig. 6: Comparison between measured and calculated pressure drops over an ARCON HT solar collector using a 40% propylene glycol/water mixture (left) and pure water (right).

A model to evaluate the flow distribution in the entire solar collector field is presently under development.

Additionally, the influence of flow rate and tilt angle on the collector efficiency has been investigated in a solar collector test facility through efficiency testing of two ARCON Solar collectors , one with (model HT-SA 35-10) and the other without FEP foil (HT-A 35-10) as convection barrier. The aim is to develop overall efficiency expression formulations as a function of both parameters, which can then be used to predict the collector efficiency in various combinations of flow rate and tilt angle. Many measurements collected between 2012 and 2013 have been analysed and the impact of flow rate on the efficiency of the two different collectors has been derived. More detailed information about this study is presented by Bava and Furbo (2014).

2.6 Flexible hydraulic concepts and stagnation prevention

The PhD project at the University of Innsbruck will be made by Alireza Shantia and supervised by Prof. Wolfgang Streicher. This study aims at developing a modular tool for analyzing complicated thermo-hydraulic networks with the focus on pressure drop and thermal losses/gains. The project will be embedded into the applied research and software development for hydraulic systems and will be validated for smaller scale hydraulic systems as well as full scale collector arrays using the hydraulic test bench at the Unit for Energy Efficient Buildings of the University of Innsbruck.

Hydronic systems are integral parts of energy systems; the term “Hydronic” is generally applicable to systems with non-linear behavior of heat and mass transfer due to using single or multiple thermo-hydraulic fluids. The interaction between hydronic components along with thermal features leads to further complex behavior. From the system perspective, it is also crucial to consider the dynamic effect of controlling equipment over flow distribution at full/part loads to ensure no unbalancing occurs in the system. Balancing is an important aspect in hydronic design that deals with preventing excessive flows/too small flows in circuits of a hydronic system. However, this interactive behavior has been usually overlooked and reduced to a strictly thermal problem in the prevalent energy simulation tools for buildings and HVAC systems such as TRNSYS or EnergyPlus by assuming a perfect hydronic behavior. Similarly, purely hydronic tools typically do not consider the dynamic thermal interaction between components imposed by controlled parameters outside system boundaries. This can be, for instance, temperature or humidity level in a room or outlet temperature in a solar field when solar insolation fluctuates during the daytime.

The project started with a literature review and analysis of which modelling environments should be used as the platform of the project. The first step was to model a simple but still comprehensive hydronic system in terms of having key hydronic components such as pump, control valves, and balancing valves in TRNSYS and Matlab® Simulink®. The model consists of two building blocks with parallel hydronic circuits connected to the heating plant and pumping system; the room temperature in each block is stabilized by the user-defined control valves as a result of varying the hydronic operating point. It was learnt that many user-defined functions should be defined to be able to consider the interaction between the hydronic and thermal parts. On top of that, modelling parallel flows in TRNSYS is a challenging task as it necessitates internal iterations within the main iteration in each time step in order to calculate the correct flow distribution. Using Carnot blockset library in Matlab® Simulink® provides more flexibility for the same model owing to the existing hydronic elements. However, it was revealed that Carnot could fulfill the requirements when it comes to elaborated hydronic systems with unknown/variable flow direction in some segments.

The recent task was to study the distribution of parallel flows in a polymer flat collector, using Simscape library in Matlab® Simulink®, for two cases regarding the local pressure loss coefficient (K) in junctions. The first case considers constant coefficients as a conventional method for estimating the pressure drop in hydronic circuits. In the second case, however, the pressure loss coefficients are calculated separately in each junction based on the passage area and velocities at inlets/outlets using empirical methods (Idelchik, 2007). Comparing the results for either case in Fig. 7 (left) highlights that assuming constant pressure loss coefficient in the junctions not only gives rise to overestimating the overall pressure drop but also results in a completely different flow distribution pattern in the strings. The variation of the pressure loss coefficients in the junctions as well as the equivalent values for the absorber strings and supply/return headers is shown in Fig. 7 (right).

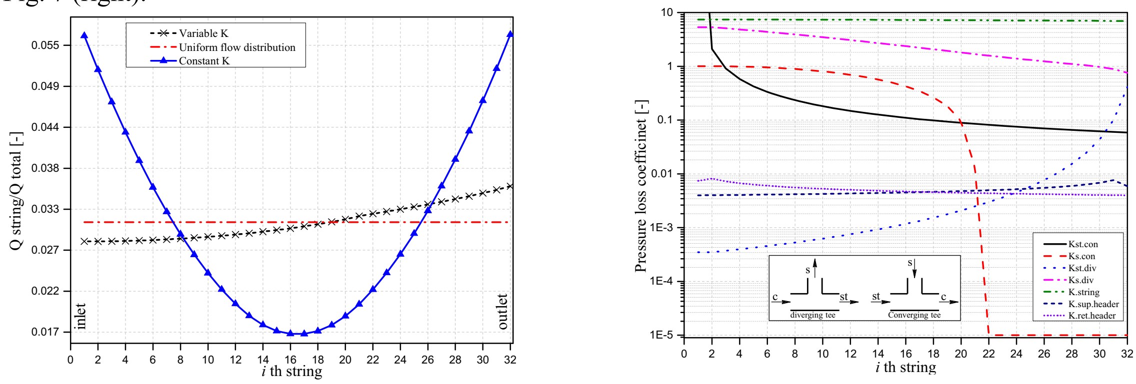


Fig. 7: Flow distribution in two cases (left) and pressure loss coefficient variation (right).

2.7 Decentralized heat supply in district heating systems

This PhD project is part of the Swedish national research school, Reesbe, and will be made by Gunnar Lennermo at the consultancy company WSP and is supervised by Björn Karlsson at Mälardalen University. There is a rising interest for the integration of decentralized heat supply in district heating (DH) systems in the form of so-called prosumers, i.e., customers that both can withdraw and supply heat to the grid. The interest comes from a growing interest in local energy supply among owners of property as well as a growing awareness among DH companies about the need to view their customers more like partners rather than just consumers of heat. If a customer wants to use solar heat it always affects the DH-grid in one way or another. One part of the work is to define different kinds of way to connect solar heating system to the DH-grid, both on the secondary and the primary side.

There are four principle ways to connect on the primary side of the DH grid;
R/R – return/return – the heat is put in to the return pipe to any level. The heat can be raised by 4 to 20 K.
R/S – return/supply – the heat is put in on the supply pipe at a fixed level (decided often by DH grid owner).
S/S – Supply/supply – is very seldom used but can be used as an over temperature discharge system instead of stopping the solar circuit
S/R – Supply/return – is very seldom used but can be used as an over load temperature discharge system without using a pump.

The feed-in system that in most cases is best for the DH-grid is the R/S-system. In Sweden there are about 30 systems of this kind. 20 of these where analyzed by Dalenbäck et al. (2013), who stated that the performance was lower than excepted. One reason for this is a problem in the control. To make this kind of system better we need to know the conditions for the heat feed in pump at the decentralized heat resource. One problem is to know the differential pressure between the supply and the return pipe in the DH network. We need to know the variation in the short and a long perspective and to this end monitoring equipment has been installed in a few of these systems and data is now being collected.

One problem identified so far is that when the pressure rise provided by the pump is lower that the differential pressure in the DH grid there is no flow and when it is higher the flow is too high. From no flow to too high flow is 1 – 5 % of the pump speed, which is the controlled variable for the control system.

There are two methods to control the primary flow using the matched flow principle in order to supply a given temperature to the supply side of the DH grid. These are shown in Fig. 8, with two-way valve (left) and three-way valve (right). Tests and calculations will be made to see which of these perform best.

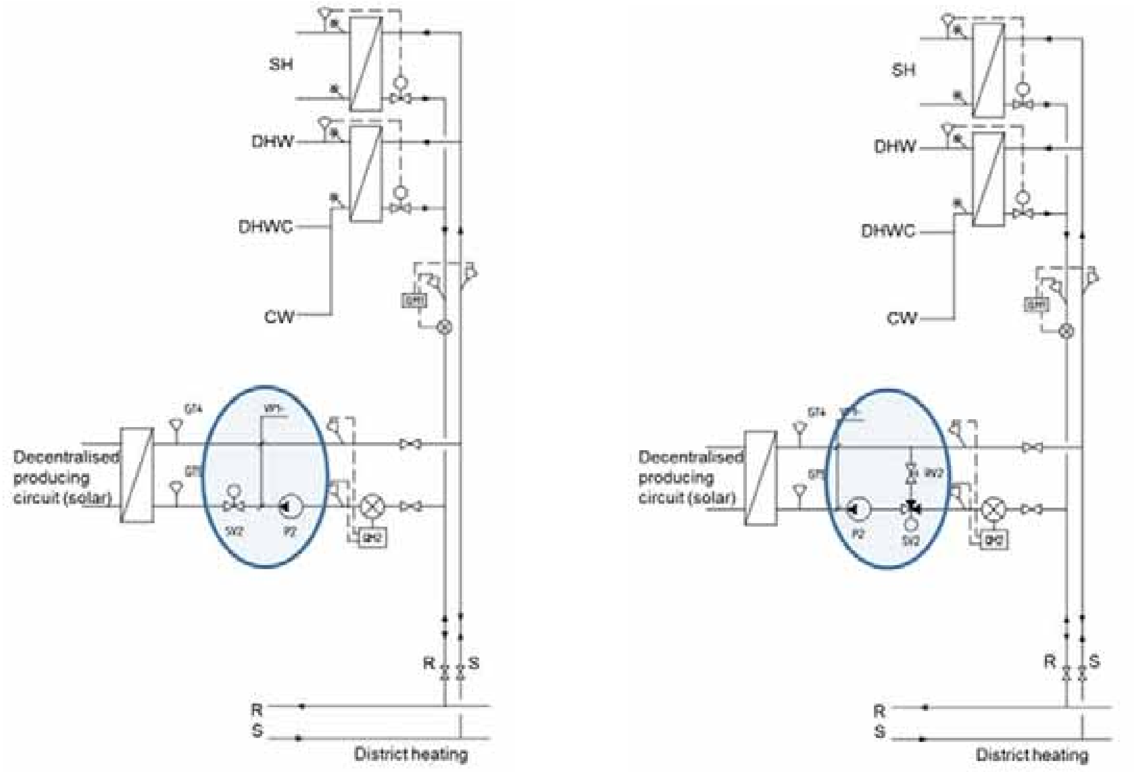


Fig. 8: Schematic of feed-in system with control with two-way valve (left) and three-way valve (right).

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