EFFSTOCK 2009, Stockholm, Sweden, June 14-17 2009

VALIDATION OF A COMPUTER MODEL FOR SOLAR COUPLED DISTRICT HEATING SYSTEMS WITH BOREHOLE THERMAL ENERGY STORE

J. Nußbicker-Lux[1)], W. Heidemann[1)], H. Müller-Steinhagen[1), 2)]

[1)] Institute of Thermodynamics and Thermal Engineering (ITW), University of Stuttgart
Pfaffenwaldring 6, D-70550 Stuttgart, Germany
Tel. +49-(0)711-685-63536, Fax: +49-(0)711-685-63503
nussbicker@itw.uni-stuttgart.de

[2)] DLR Stuttgart, Institute of Technical Thermodynamics (ITT), Germany
Pfaffenwaldring 38-40, D-70569 Stuttgart, Germany

ABSTRACT

Using measurements acquired from the Neckarsulm Borehole Thermal Energy Store (BTES) the Superposition Borehole Model was closely checked. The model has for the first time been used to investigate a twice extended BTES. At a thermal conductivity of 2.3 to 2.4 W/(m·K) and a volumetric heat capacity of 2.85 MJ/(m³·K) the correlation between measured and calculated data was best, i. e. the maximum difference between heat quantities was about 3%, while the maximum difference between temperatures was about 3 Kelvin. To calculate the thermal behaviour of the solar coupled district heating system in Neckarsulm a TRNSYS simulation model was developed. The correlation between measured and calculated heat quantities was good (<5%). Dimension guidelines for solar coupled district heating systems with BTES were derived with a TRNSYS simulation model. They take both weather data as well as the heat load and the temperatures of the district heating network into consideration.

1. INTRODUCTION

Installations encompassing Borehole Heat Exchangers (BHE) have recently gained in interest. For detailed planning validated calculation models play a crucial part in determining the thermal behaviour of installations especially those equipped with Borehole Thermal Energy Stores (BTES). With this in mind the validation of the "Superposition Borehole Model" (SBM) was undertaken. The SBM model is regarding number, type and hydraulic coupling of the BHE one of the most versatile applicable models. This paper describes how the model has been used to investigate a twice extended BTES for the first time using measurements acquired from the Neckarsulm heat store. A parametric analysis was conducted and the results were used to calculate the thermal behaviour of the solar coupled district heating system. Therefore a TRNSYS simulation model was developed and the validation was conducted using data measured in 2004.

The solar coupled district heating system in Neckarsulm consists presently of about 300 flats (in 2004: 270 flats), a shopping centre, a school with gymnasium and two residential homes for the elderly. Solar thermal collectors with a total area of 5 670 m² respectively 3.97 MW_{th} (2004: 5 263 m², 3.38 MW_{th}) are installed at various buildings, a carport and at a noise barrier. The BTES has been extended twice (1998 and 2001) and now has a volume of 63 360 m³. The borehole heat exchangers used to charge and discharge the BTES consist of double-U-pipes. Figure 1 shows the layout of the district heating system. The BTES is directly connected to the heat distribution network and charged by the solar collectors by means of two 100 m³ buffer tanks. The two buffer tanks are used for short-term heat storage to balance peaks in heat delivery from the solar collectors. The buildings are connected to the district heating system via a 3-pipe heat distribution network. The heat distribution network is supplied either by the buffer tanks or the BTES, depending on the temperature level. A condensing gas boiler supplies additional heat to provide the required temperature level.

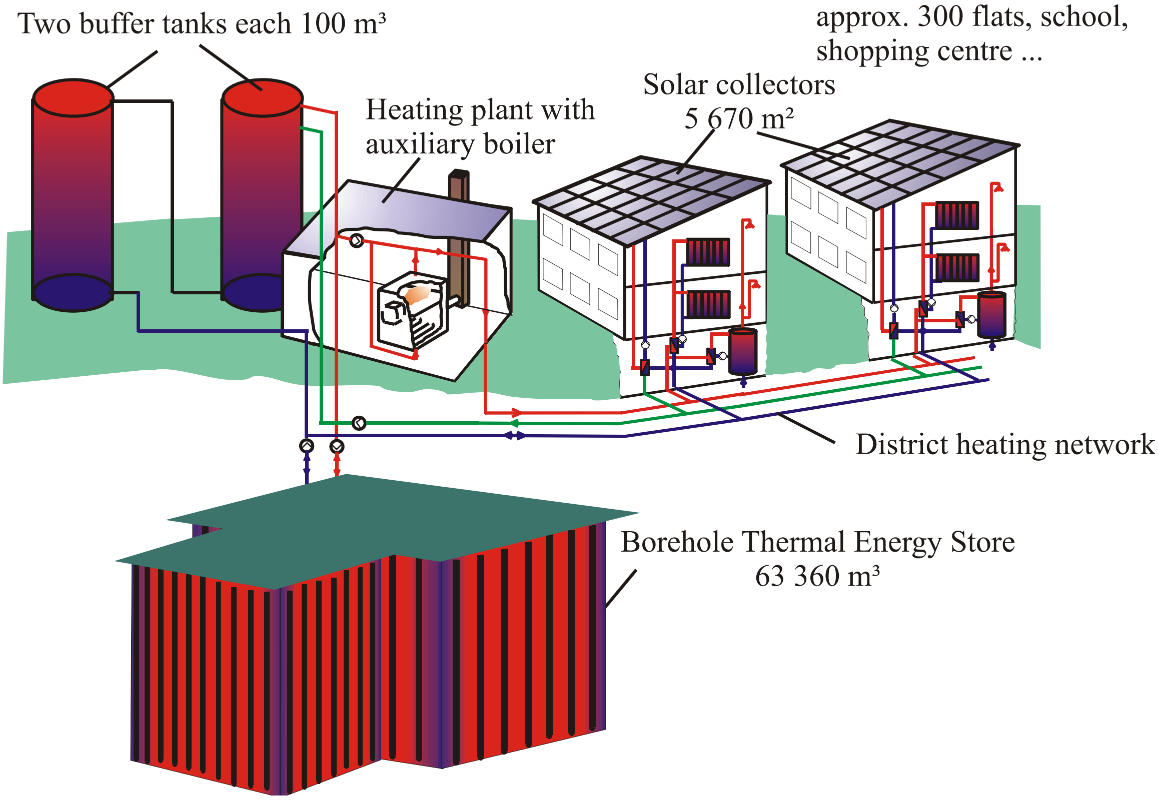

Figure 1: Layout of the district heating system in Neckarsulm

2. VALIDATION OF THE SUPERPOSITION BOREHOLE MODEL

Given the existing geometry and hydraulic storage parameters a reference model was defined into which measured storage input temperatures, flow rates and weather data were entered, see figure 2. For the period 1997 to 2003 a rough parametric analysis was conducted. Based on the best result (lowest difference between temperatures) the temperature distribution in the ground was saved at the end of the simulation. Due to high computing time and frequent malfunctions occurring during data acquisition in 1997 to 2003 the detailed parametric analysis was only based on the 2004 measurements. The temperature distribution was also used for the system simulation of the district heating system in Neckarsulm.

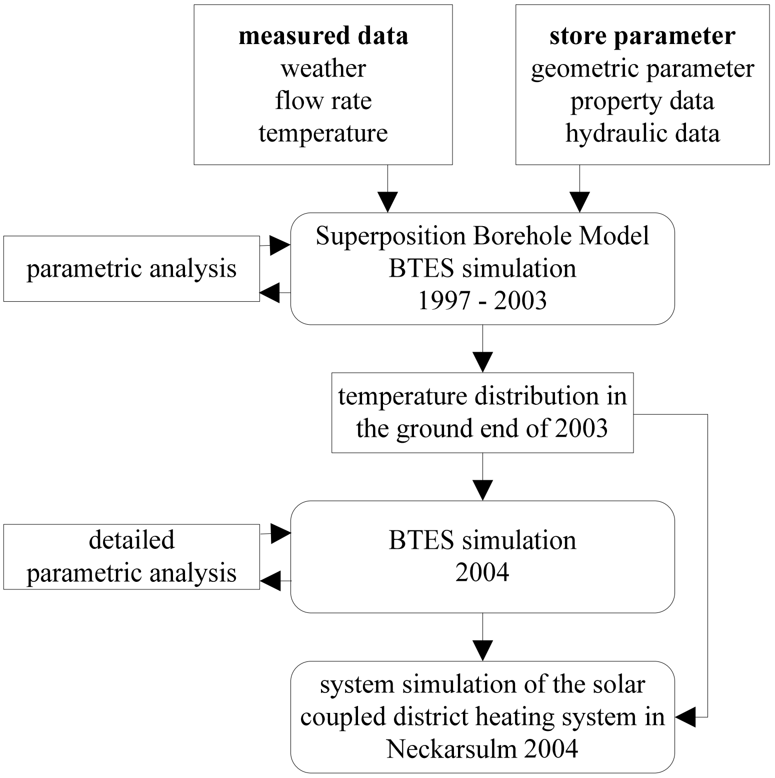

Figure 2: Procedure of the SBM validation

Figure 3 shows the layers used for the SBM validation. The first layer with a depth of 3 m consists of fill, underlain by thermal insulation (polystyrene) with a thickness of 0.2 m. The third layer is the BTES with a depth of 30 m followed by a dolomite layer of 5 m thickness and a marl layer which was assumed to have a thickness of 100 m. Figure 4 displays the relative change of the storage efficiency versus the relative change of the different ground thermal conductivities (without the BTES layer). The thermal conductivity representing insulation was set at a wide range to simulate both “perfect” and “no” insulation. The reference thermal conductivity ($\lambda_{Ref.}$) of the insulation is 0.06 W/(m·K). A BTES with no thermal insulation would have an approximately 25% lower storage efficiency while a BTES with very low heat losses due to good thermal insulation would have a 11,4% higher storage efficiency. The influence of the thermal conductivity of the layers 1 and 5 on the storage efficiency is low (<1%), whereas the influence of the thermal conductivity of layer 4 and 2 is greater. At 40% lower thermal conductivity 4% higher storage efficiency is achievable. Similary a 40% higher thermal conductivity results in 2.5% less storage efficiency.

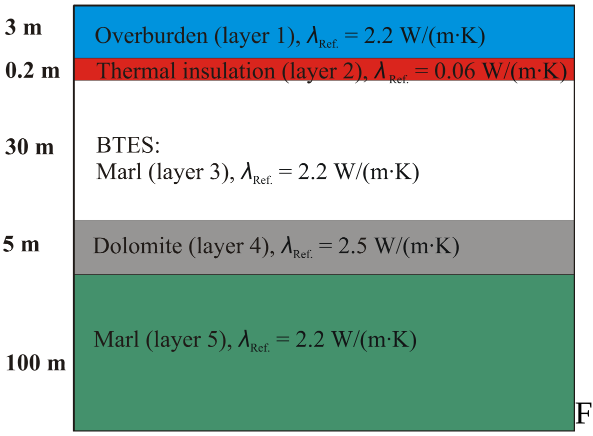

Figure 3: Ground layers considered in the SBM model

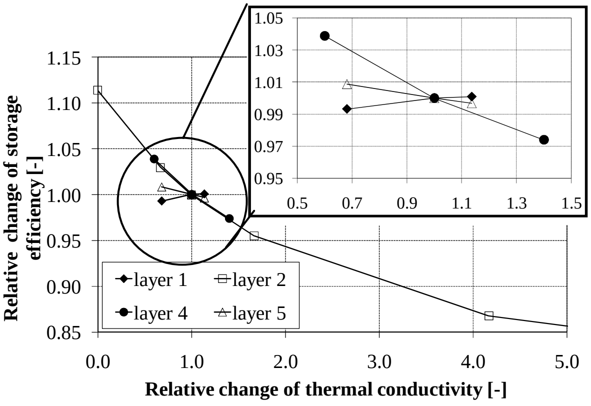

Figure 4: Relative change of the storage efficiency versus relative change of different ground thermal conductivities

Figure 5 demonstrates the relative change of the storage efficiency in relationship to the change of other parameters. The Borehole Thermal Resistance (R_b) is calculated with a program called BOR using the investigated parameters. The R_b values are then imported into the SBM model. The U-pipe spacing and the thermal conductivity of the grouting have been shown to have the highest influence on the storage efficiency. 10% less or greater U-pipe spacing will respectively result in 0.7 - 0.8% lower or higher storage efficiency. The U-pipe spacing influences the thermal interaction between the U-pipes which affects the charging and discharging amount of heat.

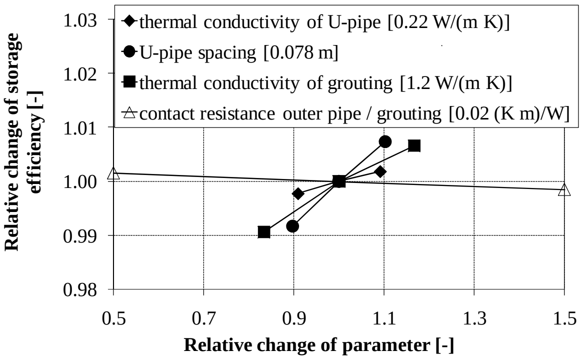

Figure 5: Relative change of the storage efficiency versus relative change of different BOR parameters

Figure 6 shows the relative change of the storage efficiency in relationship to the relative change of the volumetric heat capacity and the thermal conductivity of the BTES layer. The reference volumetric heat capacity is 2.85 MJ/(m³·K) and the reference thermal conductivity is 2.2 W/(m·K). For example a heat capacity of 2.5 MJ/(m³·K) and a thermal conductivity of

1.5 W/(m·K) results in 8% higher storage efficiency than the reference values. Similarly a thermal conductivity of 3.5 W/(m·K) results in 15% less efficiency than the reference values. At a thermal conductivity of 2.3 to 2.4 W/(m·K) and a volumetric heat capacity of 2.85 MJ/(m³·K) the correlation between measured and calculated data was best.

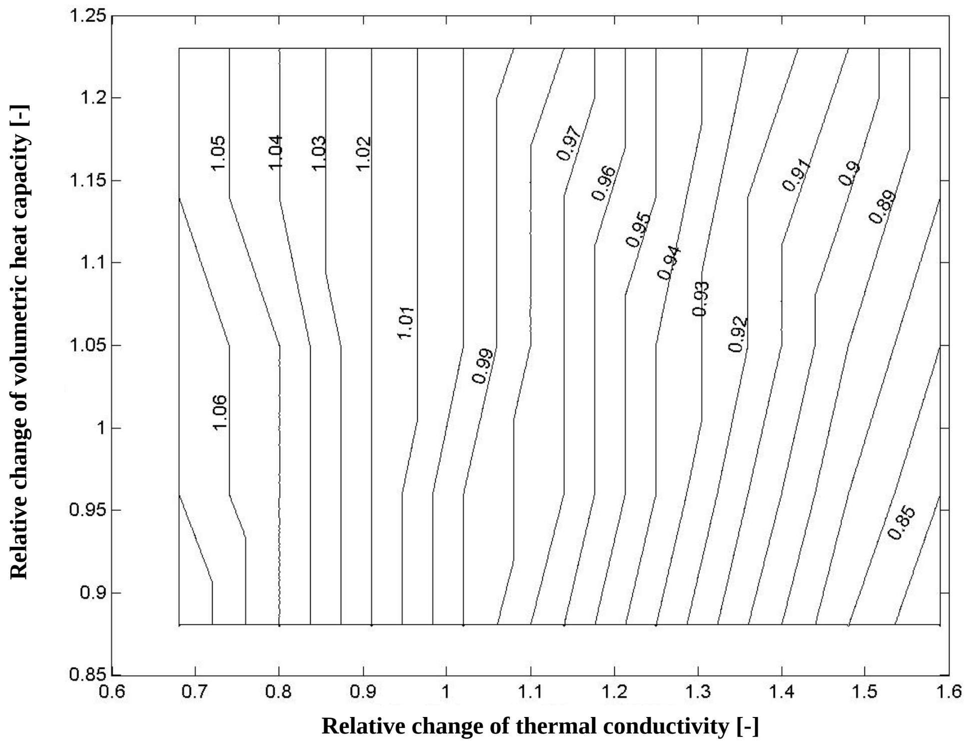

Figure 6: Relative change of the storage efficiency against the relative change of the heat capacity and thermal conductivity (BTES layer)

Figure 7 displays measured and calculated temperatures at a depth of 10 m at five locations within the 1st and 2nd extension area and at 5 m south of the BTES. At the three locations within the 2nd extension area the correlation between measured and calculated temperatures is quite good, about 3 Kelvin. At the 1st extension area the difference is a little higher (5 Kelvin) namely at the start of the simulation when importing the temperature field (see above). Ultimately the maximum difference between heat amounts was about 3%.

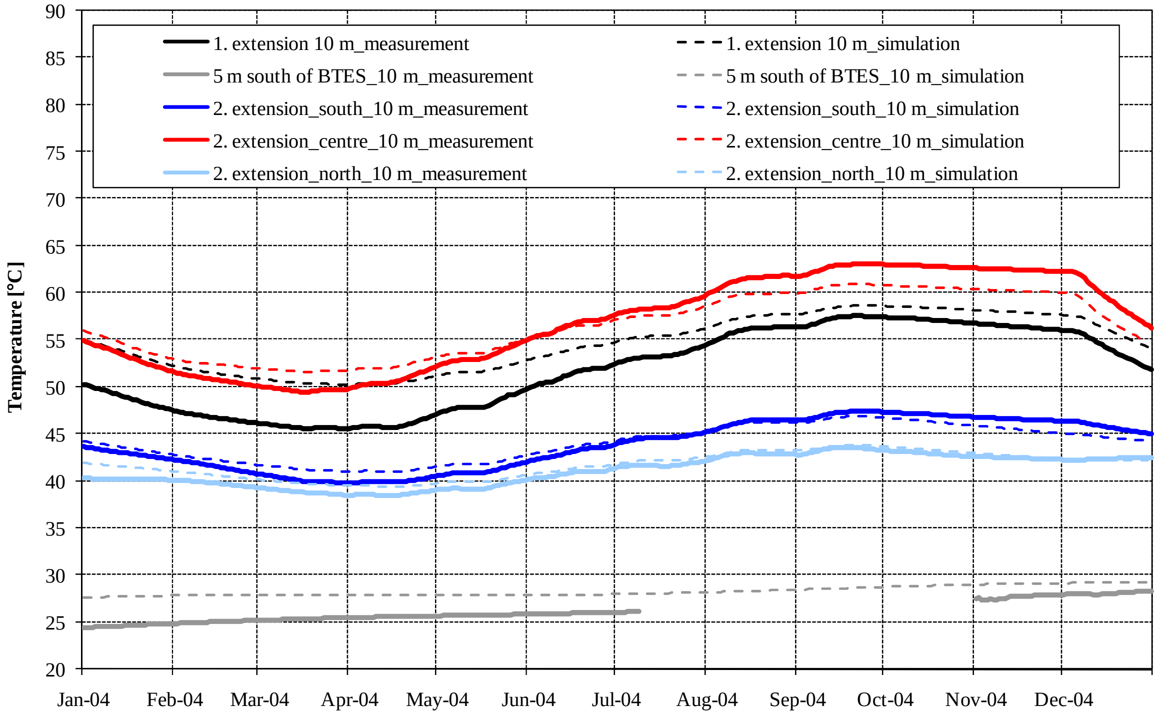

Figure 7: Measured and calculated temperatures at a depth of 10 m at different locations

3. TRNSYS MODEL FOR A DISTRICT HEATING SYSTEM

When designing solar coupled district heating systems simulation models are essential to investigate different system layouts. For example the correct choice of the thermal stores, the type of solar collectors and their hydraulic integration has to be made. After installation simulation models are useful to optimise the system and the control without interruption of the heat delivery. Figure 8 shows a diagram of the TRNSYS simulation model applied to the solar coupled district heating system in Neckarsulm. Altogether the simulation model encompasses eight solar collectors and eight solar circuits, the Borehole Thermal Energy Store (SBM) for seasonal heat storage, a buffer tank for short-term heat storage, a gas boiler, the distribution network and the control system. Measured weather and heat load data from the Neckarsulm system (year 2004) were imported into the TRNSYS simulation model.

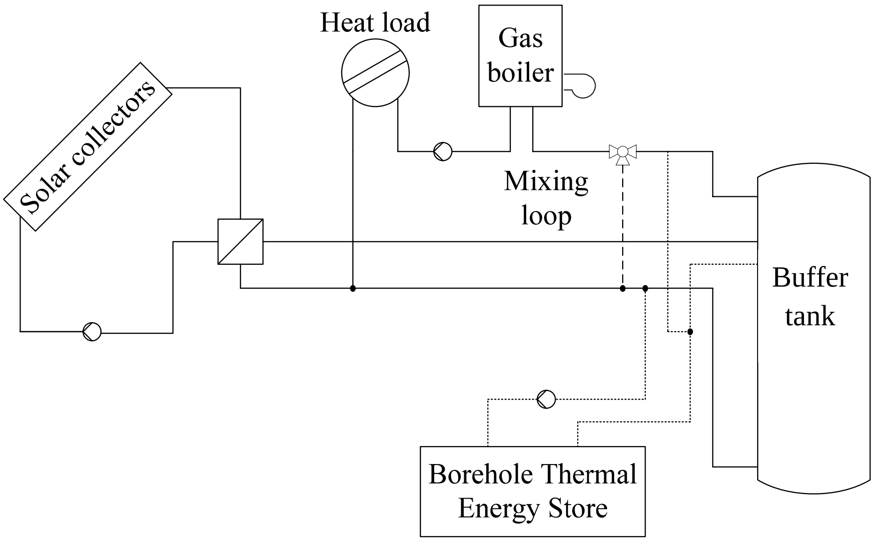

Figure 8: Diagram of the TRNSYS simulation model for the solar coupled district heating system

Figure 9 compares the measured and calculated heat quantities and shows their differences. The differences are less than 5% except for the BTES discharge heat quantity and the heat losses. Contrary to the calculations in chapter 2 the BTES flow rates are provided by the control system of the simulation model and are not measured values. Since the calculated solar heat quantity is higher than the measured solar heat quantity the calculated BTES heat discharge quantity is higher. The heat losses are not measured but were obtained from the heat balances.

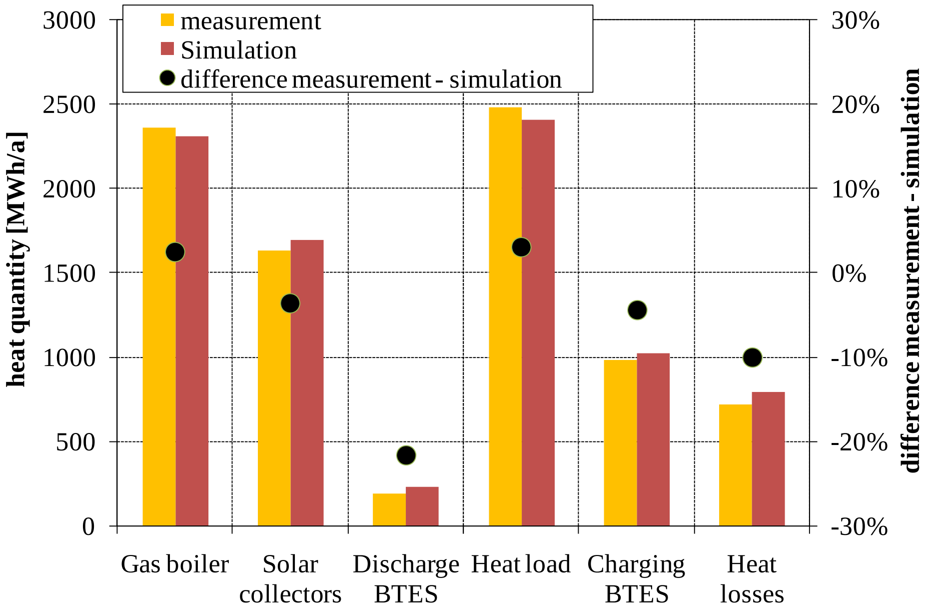

Figure 9: Measured and calculated heat quantities and their differences

4. DESIGN GUIDELINES

Dimension guidelines for solar coupled district heating systems with BTES were derived with the help of the universally applicable TRNSYS simulation model. Unlike the simulations in chapter 3 the dimensions is one solar collector and the distribution network consists of four pipes (district heating and solar supply and respective return pipes). To calculate the thermal behaviour of the BTES the "Duct Ground Heat Storage Model for TRNSYS" (TRNVDST) was used. This model distributes the BHE automatically uniformly in the cylindrical storage volume. The simulation model takes both the location (weather data from Frankfurt/Main, Würzburg and Hamburg) as well as the heat load of the district heating network at temperatures of 68/41°C and 60/30°C into consideration. TRNSYS METEONORM weather data were used. The heat load data were taken from literature.

Figures 11 and 12 depict solar fractions versus heat demand determined for the location "Würzburg" at district heating network temperatures of 68°C (supply) and 41°C (return) respectively 60°C and 30°C. The figures provide the collector area (AKoll) and the storage volume V for a given heat demand and solar fraction. The storage volume is given in relation to the collector area (V/A) which means with a collector area of 500 m² and V/A = 10 the storage volume V amounts to 5 000 m³.

The figures 11 and 12 show that the solar fractions are lower for the higher network return temperatures. With a heat demand of 5 000 MWh/a and a collector area of 10 000 m² (V/A = 10) the solar fraction is 38,3% for the 68/41°C and 43,8% for the 60/30°C return temperatures.

Hamburg represents a location with low solar irradiation while Würzburg can be regarded as a location with high solar irradiation. For example with a heat demand of 5 000 MWh/a, a collector area of 20 000 m² and a storage volume of 200 000 m³ a solar fraction of 51.4% would be achieved in Hamburg at a district heating network temperature of 68/41°C, while a solar fraction of 70.8% would be achieved in Würzburg at a temperature level of 60/30°C.

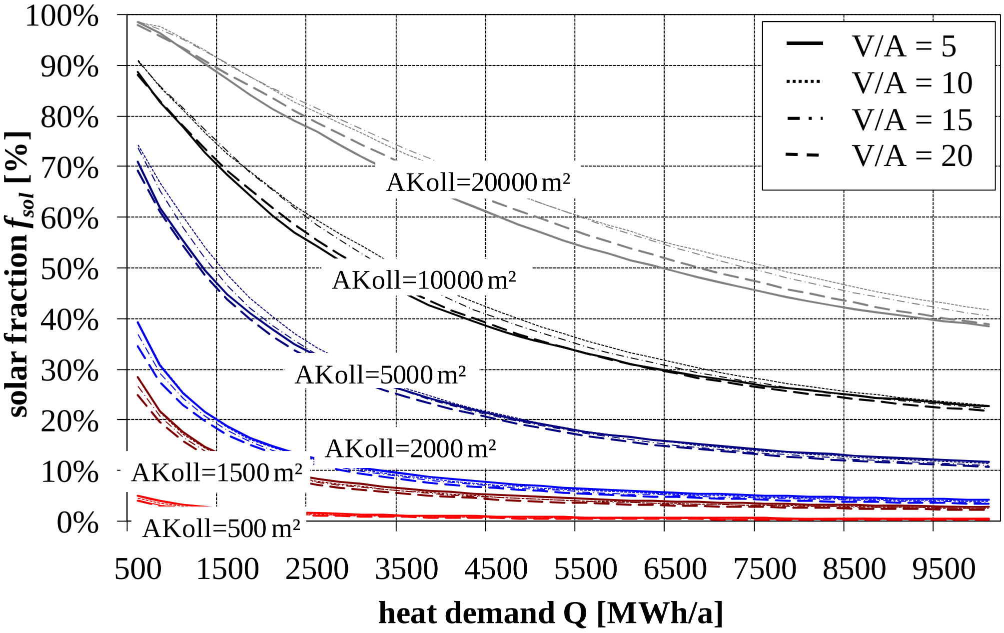

Figure 11: Solar fraction versus heat demand determined for the location "Würzburg" (Germany) and district heating network temperatures of 68°C (supply) and 41°C (return)

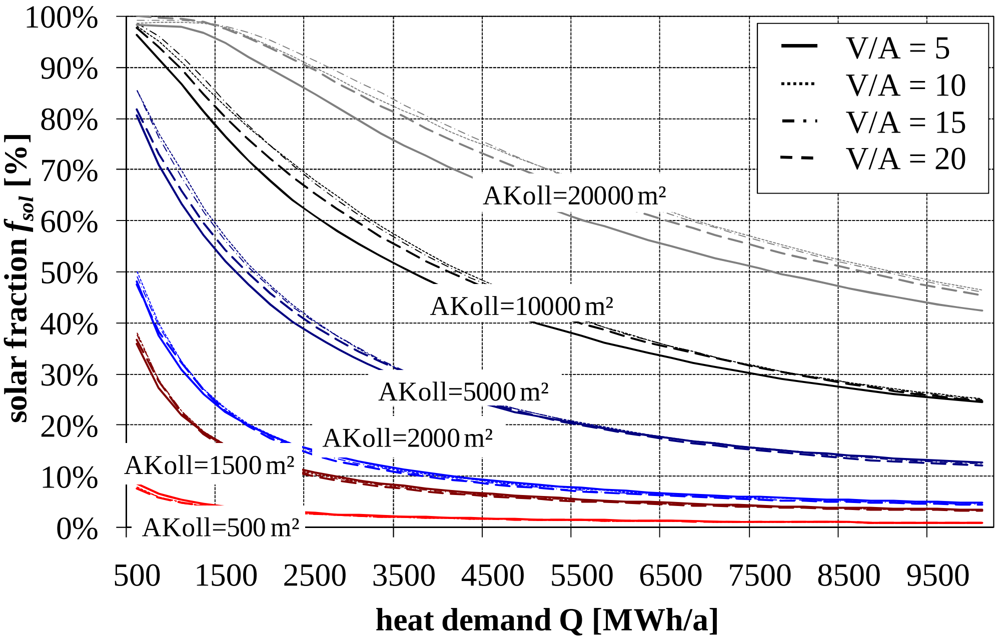

Figure 12: Solar fraction versus heat demand determined for the location “Würzburg” (Germany) and district heating network temperatures of 60°C (supply) and 30°C (return)

ACKNOWLEDGEMENTS

The realisation of the demonstration project and the ongoing scientific work has been / is supported by different German ministries (BMBF, BMWA, BMWi, BMU). The authors gratefully acknowledge this support and carry the full responsibility for the content of this paper.

REFERENCES

Eskilson, P. (1986). Superposition Borehole Model, Manual for Computer Code, Department of Mathematical Physics, University of Lund, Lund, Schweden.

Pahud, D.; Hellström, G.; Mazzarella, L. (1996). Duct Ground Heat Storage Model for TRNSYS (TRNVDST), User Manual, LASEN-EPFL, Lausanne CH.

Holst, S. (1997). Type 146 TRNSBM – Modified Version for separate ground layers, TRANSSOLAR.

Pahud, D. (1997). BOR, Borehole Pre-Processor for TRNVDST in TRNSYS, Department of Mathematical Physics, University of Lund, Lund/Sweden.

Seiwald, H. and Hahne, E. (2000). Underground seasonal storage for a solar heating system in Neckarsulm / Germany. Proceedings of Terrastock 2000, 28.08.-01.09., Stuttgart, Germany, Benner, M. and Hahne, E. (eds.), pp. 213-219.

Nußbicker, J., Mangold, D., Heidemann, W. and Müller-Steinhagen, H. (2003). Solar assisted district heating system with duct heat store in Neckarsulm-Amorbach (Germany), Proceedings of ISES Solar World Congress 2003, Göteborg (Schweden), 14.-19.06.2003.

Bodmann, M., Mangold, D., Nußbicker, J., Raab, S., Schenke, A., Schmidt, T. and Müller-Steinhagen, H. (2005). Solar unterstützte Nahwärme und Langzeit-Wärmespeicher, Forschungsbericht zum BMWA / BMU-Vorhaben 0329607F, Solar- und Wärmetechnik (SWT) Stuttgart.

Raab, S. (2006). Simulation, Wirtschaftlichkeit und Auslegung solar unterstützter Nahwärmesysteme mit Heißwasser-Wärmespeicher, D93 Dissertation Universität Stuttgart, Cuvillier Verlag Göttingen.