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Emulated Borehole Heat Exchanger for Comparison of Different TRT Units

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ABSTRACT

To fulfill the UNFCC-Paris Agreement, shallow geothermal energy will play a major role in the future. For optimal usage of the geothermal potential, a precise estimation of the underground thermal properties is required. The Thermal Response Test (TRT) is a well-established method to measure the relevant underground data. So far, there has been no possibility to check and calibrate the TRT rigs which are mostly built in a self-made version. At the ZAE Bayern, an emulated borehole heat exchanger (E-BHE) to objectively check TRT units under adjustable and comparable underground conditions, has been developed, constructed and experimentally determined. The E-BHE consists of a chiller, a thermal storage tank and two heat exchangers with an electrical heater downstream for fast-acting regulation of the outlet temperature. It uses a regulation concept together with a borehole heat exchanger model. First tests have been conducted with thermal conductivities of the underground between 2.15 and 4 W/mK, borehole lengths between 80 and 100 m and undisturbed ground temperatures between 10 and 12°C. These varying parameters have been adjusted as default values at the E-BHE. One set of data used corresponds to the values measured at a real borehole heat exchanger (BHE) over the past several years by a high precision TRT constructed at the ZAE Bayern. During the five tests, this TRT unit has been connected to the E-BHE and showed deviations in determined thermal conductivity of only 2.4 % +/- 2.2 % compared to the default values of the E-BHE.

1. INTRODUCTION

During the upcoming energy revolution, the use of shallow geothermal energy will increase. Therefore, it is important to know the essential parameters of the underground such as the effective heat conductivity λ_{eff}, undisturbed underground temperature T_{ug} and volumetric heat capacity c_v. To experimentally determine these parameters, the Thermal Response Test (TRT) method was established by Jeffrey Spitler and Signhild Gehlin in the 1990s. Since then, numerous mobile devices have been developed based on the following functional principle: a certain constant heat power is brought in the underground via a fluid in a U-pipe of a test drilling. The temperature answer is measured over time [1]. In Germany a standardized analysis is done in accordance to the VDI Guideline 4640 Blatt 5 [2] adapting time-dependent data to the analytical solution of infinite line or cylinder source equations for large times. In this case, λ_{eff} results from the slope of the average fluid temperature, which is the average of measured underground temperature answer, i.e. outlet temperature and inlet temperature, if plotted against natural logarithm of time. The result of λ_{eff} has to converge for at least 20 h for a test to be valuable. Usually a three day test duration period is sufficient. An additional result is the thermal resistance R_b of the borehole. The critical point is that today's TRT units are self-made test rigs and there has been no possibility to check their reliability until now. Thereby, not only the measurement accuracy of each sensor has to be checked, also the whole TRT assembly, test implementation and evaluation procedure have to be scrutinised to determine the correct parameters of T_{ug}, λ_{eff}, R_b according to the VDI Guideline 4640 Blatt 5. Such a complete test procedure was developed at ZAE Bayern to objectively evaluate TRT units, determining their actual accuracy in T_{ug}, λ_{eff}, R_b. As a long-term objective, high precision standards for TRT devices should be formulated and guaranteed and invalid TRTs should be sorted out. Principally, it would also be possible to check the TRT units at a real and well known BHE, but this has some disadvantages for instance long waiting periods for the undisturbed ground temperature to recover to its original state, after each test, and no identical boundary conditions because of aboveground climatic influences.

Since 2016, the development was financed within the research project "Qualitätssicherung bei Erdwärmesonden II – QEWS II" (FKZ 03ET1386A) (translated: Quality Assurance for Borehole Heat Exchanger) by the German Federal Ministry for Economic Affairs and Energy. The test rig emulates a BHE to get the same time-dependent outlet fluid temperature similar to at a real BHE. The need for such a test device is emphasised by the fact that simultaneously a similar test rig was developed at the Département de genie mécanique of the Polytechnique Montréal [3]. The first results of this test rig, called virtual borehole (VBH), show a difference between heat conductivity as measured by a TRT unit to the heat conductivity as given by the test rig of 6 % [4]. Hereby the test is controlled and not regulated as in the case of this concept, the E-BHE. At a VBH, a TRT unit is connected to the VBH and a certain constant heat power in combination with a certain volume flow is adjusted by the TRT-devices. These values are passed to the VBH, where the time-dependent outlet temperature is calculated, like at an E-BHE with an integrated simulation model, but with no respect to the actual and often unstable course of inlet temperature, heat power and volume flow. This principle works well for good and stable TRT units, but for units with changes in the heat capacity or volume flow, this leads to deviations in the return temperature compared to return temperature during the same test on a real BHE. To avoid this, the E-BHE works with the principle of "Hardware in the Loop".

In the following, the emulated borehole heat exchanger (E-BHE), will be explained in detail.

2. CONCEPT AND DEVELOPMENT OF THE EMULATED BOREHOLE HEAT EXCHANGER (E-BHE)

2.1 Concept and Requirements

The test rig is supposed to simulate the thermal behaviour of a real BHE. The TRT unit shall be connected to the E-BHE in the same way as to a real BHE. With the E-BHE the following variations are possible: Different underground properties (e.g. T_{ug}, λ_{eff}, different underground layers); Different BHEs (depth of the BHE H and sort of heat exchanger (single U- and double U-pipe), R_b); Different principles of fluid heating TRT units with different regulation strategies and evaluation methods (different simulation models).

2.2 Construction and Development of E-BHE

The E-BHE essentially is built up of a chiller, which delivers the heat extraction performance to a storage tank, and two heat exchangers with an electrical heater downstream for better and faster regulation of the outlet temperature T_{out}, Figure 1.

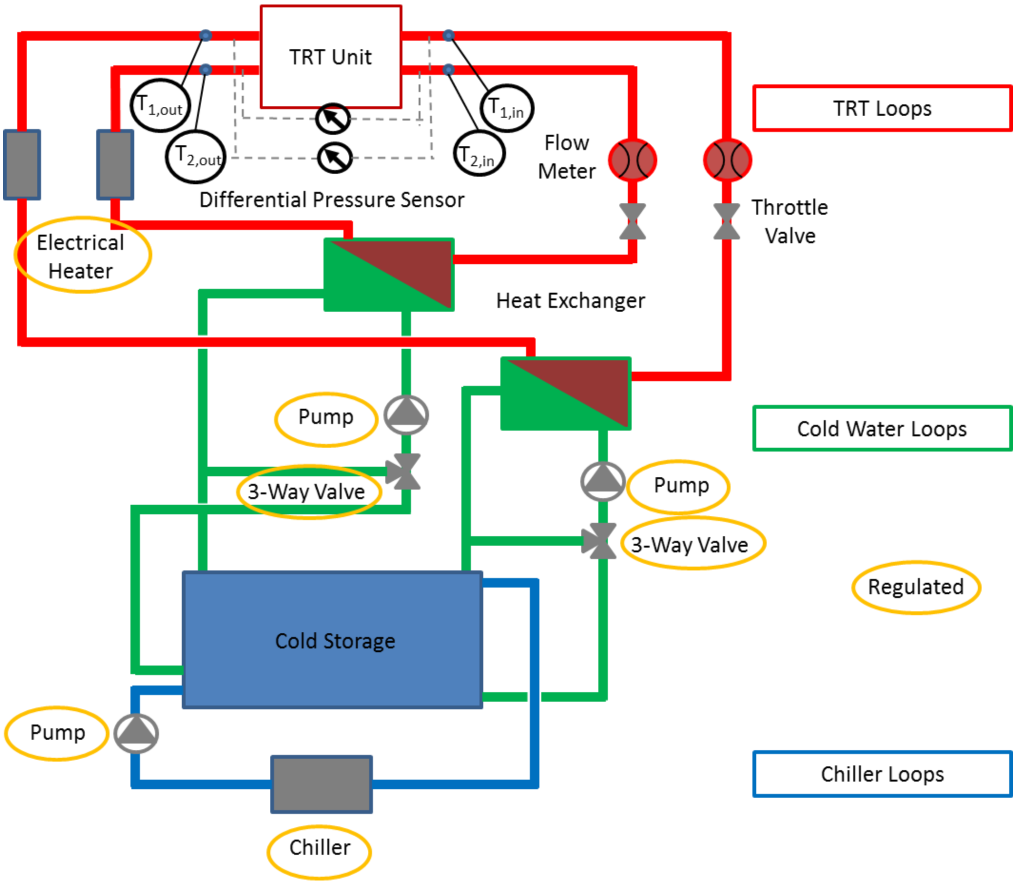

Figure 1: Hydraulic Concept of the E-BHE.

In detail, the E-BHE is characterised as follows:

- There are two TRT-loops to emulate single U- and double U-pipes, which are the most common type of BHE for TRT units. In these loops highly precise sensors for temperature and volume flow measurement are included to measure the fluid inlet and outlet temperature (T_{in}, T_{out}) as well as the volume flow $\dot{V}$ with an accuracy of +/- 0.1 K and +/-3 %, respectively, and thereby examine the measured data of the TRT unit.
- The length H of the BHE is realised by implementing a corresponding time delay in the simulation model. For the hydraulic realisation, throttle valves are integrated to simulate the corresponding pressure drop for different lengths of a BHE.
- To quasi-instantaneously obtain the required outlet temperature, the chiller always keeps the cold storage tank at a certain low temperature (6°C). The heat extraction rate of a real BHE is simulated by the heat exchangers, which are connected through the cold storage to the chiller. The volumetric flowrate in the cold water loops is regulated by variable pumps and the temperature by regulated three-way valves. The outlet temperature is roughly regulated by these heat exchangers (for practical reasons, it is regulated 0.2 K colder than the calculated value). For fine-tuning, on the other side of the heat exchanger, the outlet temperature is highly precisely (less than 0.1 K) regulated via downstream electrical heaters.
- The E-BHE works according to the principle “Hardware in the Loop”: From the point when the TRT unit starts the test, T_{in} and $\dot{V}$ are measured by the E-BHE consistently every two seconds. These values are forwarded to the simulation model, where T_{out} is calculated from the predefined underground parameters (λ_{eff}, c_v, T_{ug}, R_b, H) and the measured data. With a certain time delay (depending on H), this value is forwarded to the regulation of the E-BHE to quasi-instantaneously create the resulting T_{out}. In this way the actual timely course of the borehole inlet parameters is respected. This is the main difference from the Canadian VBH concept, where the inlet parameters ($\dot{Q}$ and $\dot{V}$) produced by a TRT unit are initially adjusted at the VBH and then considered to be unchanged during the test (undisturbed case). If fluctuations of the inlet parameters occur during the test, which is often the case, there is no possibility to react according to a real BHE´s behaviour.

This may result in deviations of T_{out} calculated for the undisturbed case and consequently to errors in the determined underground parameters.

2.3 Simulation Model

Since the 1990s many BHE simulation models were developed and validated on real borehole data. For example there is the analytical model TRNSYS TYPE 300 of Arturo Busso, which uses the Kelvin-Theory of the infinite line source [5] or the TRNSYS TYPE 451 EWS Model, which uses the “Trichterformel” of Werner [6]. Additionally, there are also more detailed numerical models. A comparative survey of important models is given for example in [6].

2.3.1 Demands upon the model

The simulation model processes the input values T_{in} and $\dot{V}$ as well as the heating power $\dot{Q}$ as measured by the E-BHE. From these values together with the set parameters of the underground and the BHE length, T_{out} has to be calculated. As a “Hardware in the Loop” test rig is desired, the calculation duration has to be faster than the time for one fluid element to get once through the set BHE length (typical values are less than 20 minutes for $H = 80\ m$ and $\dot{V} = 0.34\ \frac{m^3}{h}$ in the pipe). Under this constraint, the calculation-time intensive numerical models are not applicable.

2.3.2 Model selection

Because of its simplicity and wide dissemination, the analytical line source model TRNSYS TYPE 300 of Arturo Busso [5] is used for the first step of development.

However, the above mentioned time-delay between corresponding T_{in} and T_{out} values is not considered in the Busso model. The calculation is done at every time step with the average fluid temperature as calculated from the instantaneous values of T_{in} and T_{out}. Therefore, the simulation model had to be adjusted for the E-BHE and an extra code to the regulation concept was added. Nonetheless, this addition leads to deviations in the results for instable TRT units. Hence, a more complex model is used for the next step of development. Under discussion are the TRNSYS TYPE 451 model of Huber [6] and the B2G model of the Universitat Politecnica de Valencia [7].

3. CONSTRUCTION OF THE E-BHE

To build up the E-BHE a CAD model was constructed. The E-BHE is built up of two parts. One part is the chiller, which is connected to the cooling system. The other part includes the TRT loops together with the heat exchangers connected over the cold water loops to the cold storage tank (Figure 2).

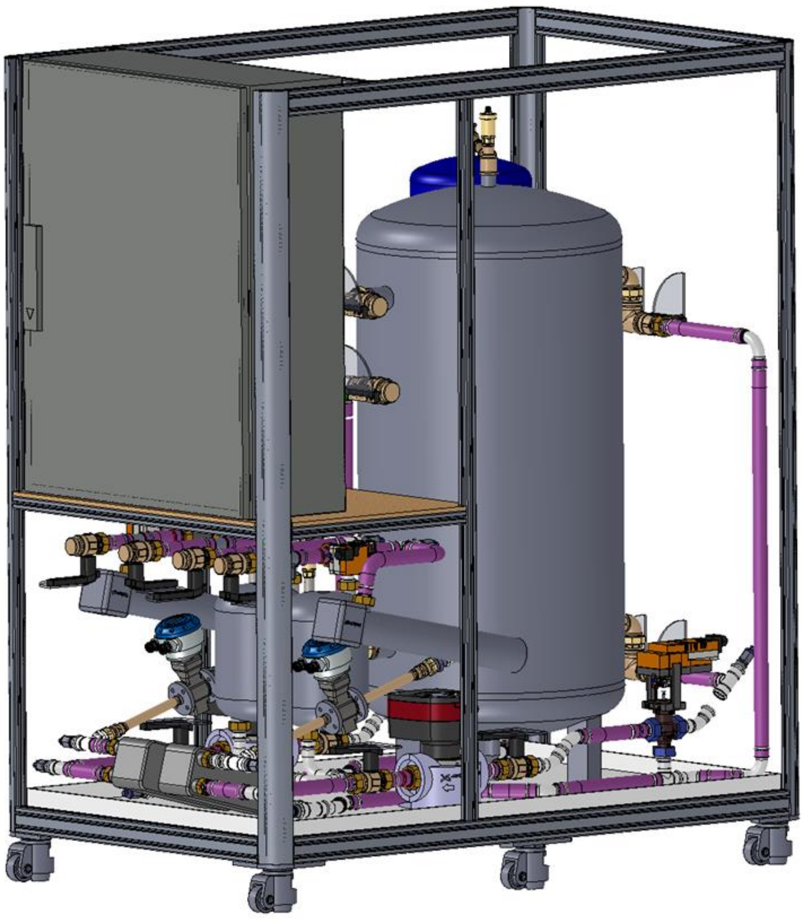

Figure 2: CAD graphic of TRT loops, cold water loops and the cold storage.

To attach TRT units to the E-BHE, connections through the laboratory-wall have been drawn, corresponding to a preferably realistic test regarding climatic conditions as occurring to an outside mounted TRT unit. A photograph of the complete E-BHE including a connected TRT unit is shown in Figure 3.

Figure 3: At the ZAE Bayern developed and built up E-BHE (left side) with a connected high precision TRT unit of ZAE Bayern (right side).

4. FIRST RESULTS AND DISCUSSION

4.1 Regulation Concept

The functionality of the regulation concept was tested with a step response. The calculated outlet temperature in a step function was decreased by 2 K. The resulting real T_{out} as generated by the E-BHE test rig as well as the set T_{out}, the regulated position of the three-way valve and the real position of the three-way valve are shown in Figure 4. It can be seen, that the regulation concept works properly. Even though T_{out} initially overshoots by 0.4 K, the new set T_{out} is reached after about 50 seconds with an accuracy of less than 0.1 K. This is an excellently quick time response and these transient deviations of only 50 s duration indeed enter the evaluation process but are negligible in comparison to 72 h total test duration. Furthermore, instantaneous temperature deviations in a TRT commonly are significantly below 2 K.

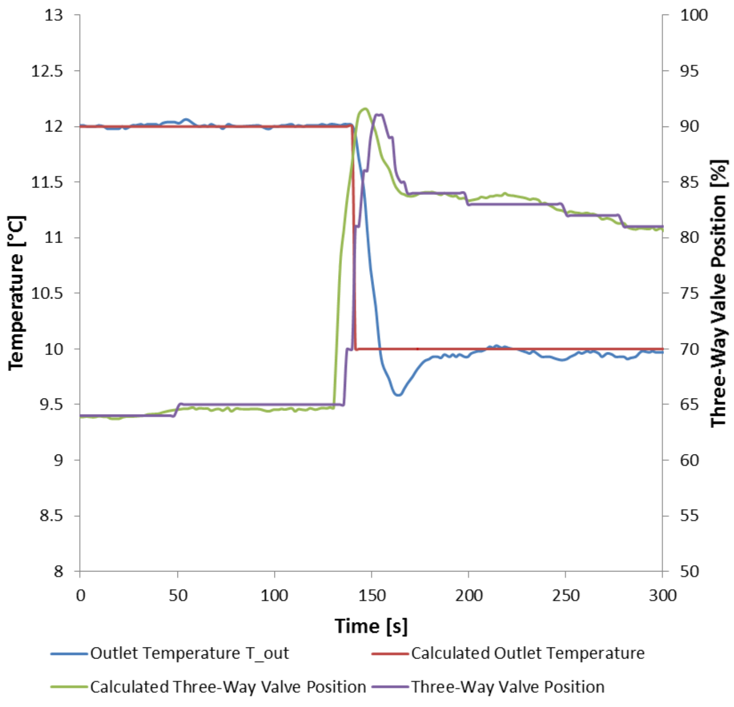

Figure 4: Experimental Step response of T_{out} to a sudden change in calculated T_{out}.

4.2 TRT measurement at the real BHE and E-BHE

In Figure 5 T_{in} and T_{out} and with them the average fluid temperature as well as the thermal power measured by the TRT unit are shown. The top graph corresponds to a TRT connected to a real BHE, while the bottom figure represents a TRT at the E-BHE. The BHE length is 80 m, $\lambda_{eff} = 2.20\frac{W}{mK}$ and $T_{ug} = 11\ °C$. These constant underground parameters have been measured over a period of almost 10 years on the same real borehole with the high precision TRT unit of ZAE Bayern, which confirms the long-term stability of this TRT unit. Additionally a geology investigation and evaluation of the TRT measurement with another evaluation method show the same result for λ_{eff} as it was done within the previous project "Qualitätssicherung bei Erdwärmesonden und Erdreichkollektoren" [8]. These values are passed as default values to the E-BHE to investigate, whether the E-BHE can emulate the real BHE regarding T_{out} and in conjunction with it also regarding λ_{eff}. Already at first glance, the measured values coincide between both tests. The larger fluctuation in the thermal power input of the E-BHE are a result of the simplified Busso model as explained above. The difference in the start temperature results from the difference between the real underground temperature and the start fluid temperature in the TRT unit connected to the E-BHE. A model addition for the first minutes is under implementation to additionally emulate the temperature distribution over the borehole length during the first complete fluid circulation corresponding to T_{ug}, if the timely course of T_{out} or the spatial distribution of the starting fluid temperatures is averaged.

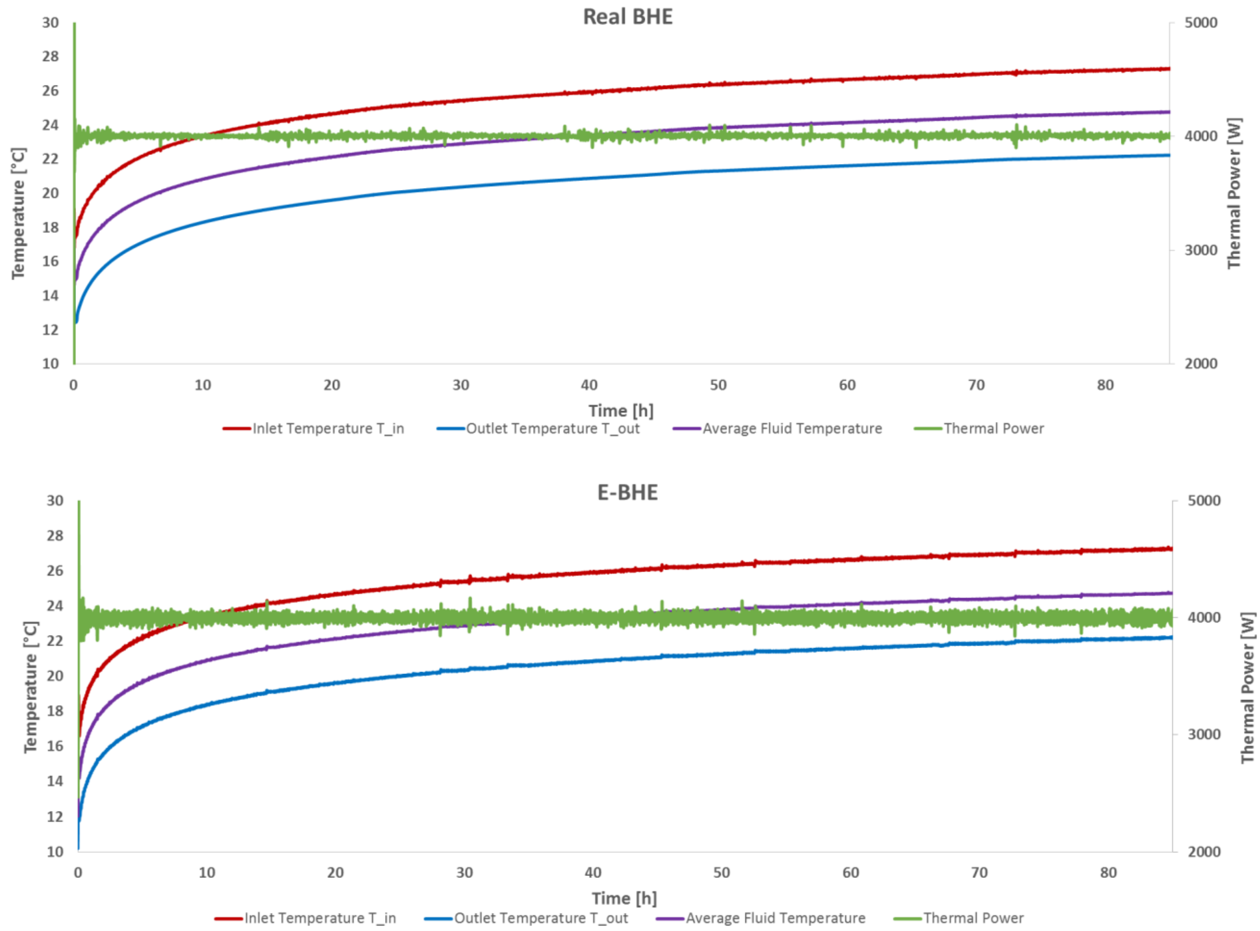

Figure 5: Above: Temperature answer of the real BHE. Below: Temperature answer of the E-BHE with corresponding underground parameters like at the real BHE.

To assess the experimental regulation functionality of the E-BHE during a complete TRT, a comparison between the set outlet temperature as calculated by the simulation model and the regulated T_{out} of the E-BHE is shown in Figure 6. The deviation between T_{out} measured and T_{out} simulated is 0.18 K on average, which again shows an excellent regulation functionality of the E-BHE as already indicated by the first positive regulation test after a 2 K step change in T_{out} (see Figure 4).

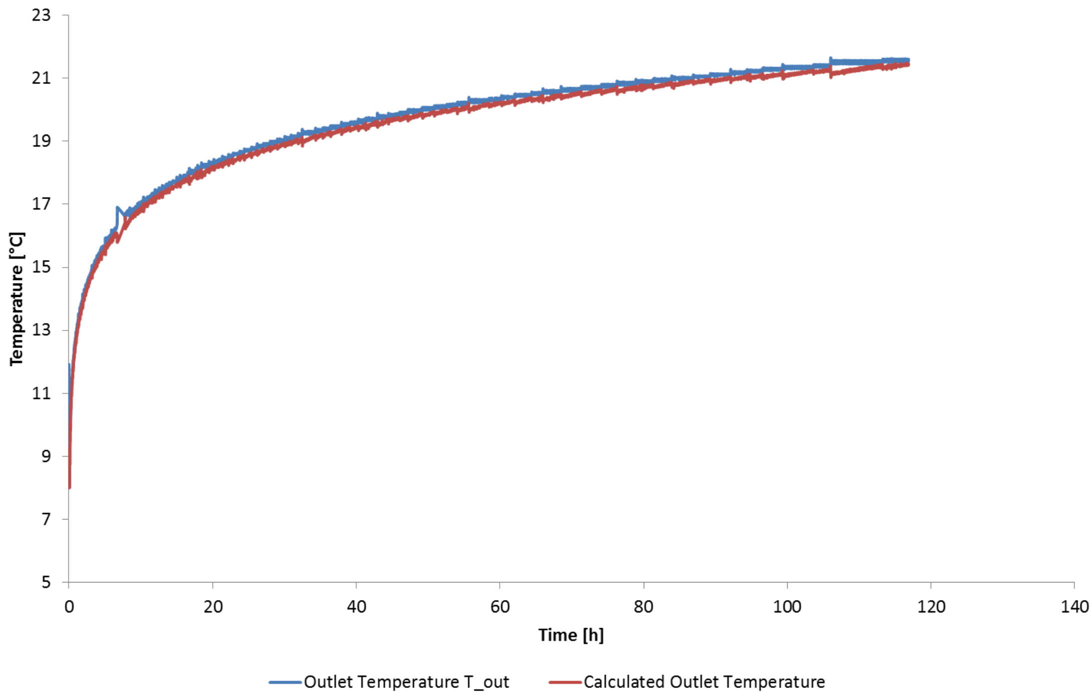

Figure 6: Comparison between measured/regulated and calculated/simulated outlet temperature T_{out}.

4.3 Evaluation of the TRT measurement at the E-BHE

The evaluation of the measured T_{out} values by the TRT unit according to VDI 4640 Blatt 5 [2] with the forward and backward convergence criterion of λ_{eff} is shown in Figure 7. As already explained above, the average fluid temperature shows a typical standard TRT course. With the backward convergence criterion, the physical minimum time of the test is detected. The forward convergence, starting from this detected minimum time, shows a perfect convergence of more than 20 h. Here, the convergence criterion is $\Delta\lambda_{eff}$ < +/-5 %. The final evaluation yields a thermal conductivity for the emulated underground of $\lambda_{eff} = 2.21 \frac{W}{mK}$. Compared to the set value for the simulation model of $\lambda_{eff} = 2.20 \frac{W}{mK}$ this corresponds to a deviation of only 0.5 %.

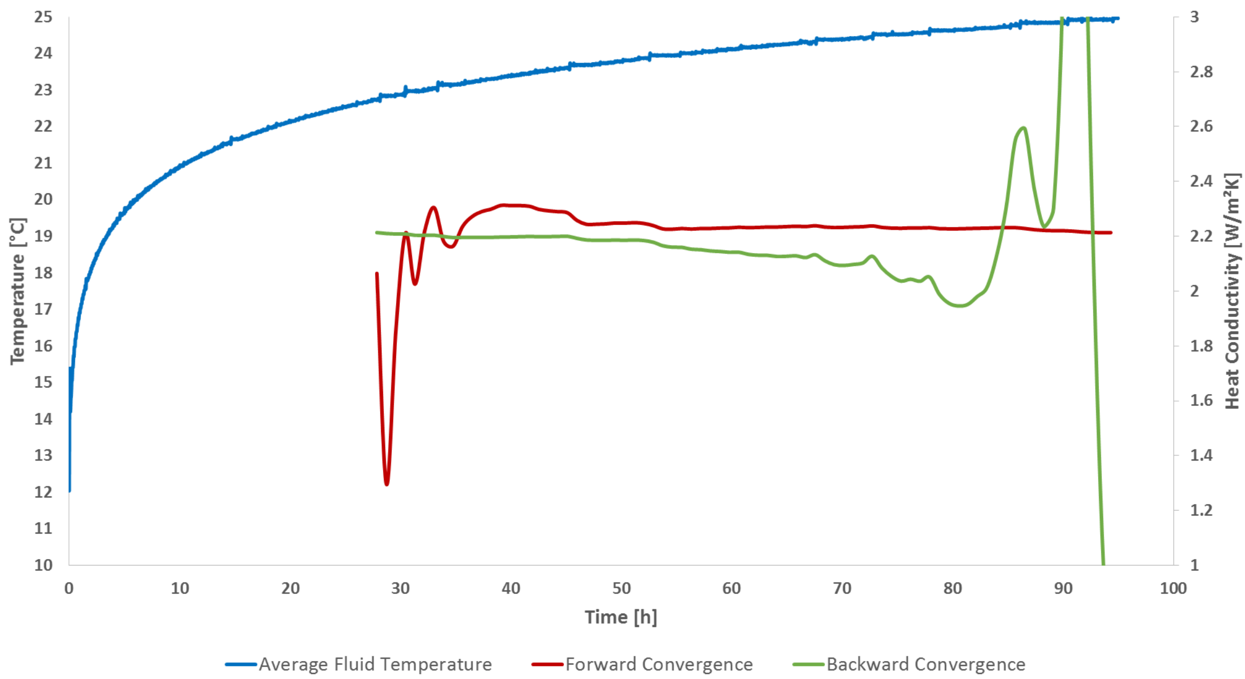

Figure 7: Evaluation of the TRT measurement at the E-BHE.

With the E-BHE it is now possible to emulate other BHE lengths and thermal conductivities. The measured results by the TRT unit also leads to slight deviations of a few percent points in comparison to the set parameters for the E-BHE. The mean percentage deviation value and its standard deviation over the five measured thermal conductivities amounts to only 2.4 % +/-2.2 %. An overview of the results is given in Table 1.

Table 1: Comparison of set and evaluated heat conductivity.

Set Values Simulation Model (E-BHE)			Evaluation Results (TRT)	Difference
$\lambda_{eff}\ \left[\frac{W}{mK}\right]$	$H\ [m]$	$T_{ug}\ [°C]$	$\lambda_{eff}\ \left[\frac{W}{mK}\right]$	$\Delta\lambda_{eff}$ [%]
2.15	80	10	2.13	1.0
2.20	80	11	2.21	0.5
3.00	100	12	2.96	1.3
3.50	80	10	3.27	6.6
4.00	100	10	3.90	2.6

The results show, that the first step of the development of the E-BHE was quite successful. For stable running TRT units, the E-BHE functions properly, as does the Canadian VBH. However, the measuring accuracy of the E-BHE is more than twice as high, which probably is consequence of our "Hardware in the Loop" concept using experimentally supported regulating instead of simple controlling.

Nevertheless, the main aim remains, to check and assess also the instable TRT units, which is currently under investigation.

5. CRITICAL ASSESSMENT OF E-BHE VERIFICATION METHOD USING THE INFINITE LINE SOURCE EQUATION

At the current state, both the used TRT device and the newly developed E-BHE are based on the same equation of infinite line source. Hence, at first glance, our proof of reliable operation of the new E-BHE looks like a circular verification of the infinite line source (ILS) equation with the ILS equation. However, in effect, the successful operation of our new E-BHE apparatus was examined by comparing the measuring results of the same TRT unit, which is first connected to the real BHE and then to the E-BHE. There an excellent agreement in T_{out}(t) was achieved, see Figure 5 and Figure 6. In addition, the value for λ_{eff} as measured by the TRT unit at the real BHE has been formerly evaluated with two different models, the ILS and the more accurate EWS model (TRNSYS TYPE 451 model [6]) and also verified with an geological survey of the drilling-core with nearly the same results. As explained above this comparison is already done in the previous project QEWS I [8]. And after that 2.20 W/mK is used as set parameter for the E-BHE. For the next steps, it is planned to also investigate TRT units basing on different evaluation processes, which do not use the ILS equation.

6. OUTLOOK

The next step of development is implementation of a more complex simulation model for the E-BHE. Suitable options are the TRNSYS TYPE 451 model of Huber [6] or the B2G model of the Universitat Politecnica de Valencia [7]. For the latter, an add-on for double U-pipes would be necessary.

After implementing the more complex model, further tests have to be done with the E-BHE to validate the functionality. Furthermore, tests with TRT units basing on different evaluation methods, i.e. different from ILS equation, should be done.

Subsequently, suitable test cycles and test ranges (T_{ug}, λ_{eff}, R_b, H) as well as test criteria shall be developed to secure a good quality for afterwards built BHE fields by guaranteeing a high quality of admitted TRT-devices for ground exploration.

7. CONCLUSION

At ZAE Bayern, an emulated borehole heat exchanger (E-BHE) was developed with a regulation concept. Simultaneously a similar test rig, a virtual borehole (VBH), was developed in Canada at the Département de genie mécanique of the Polytechnique Montréal [3], but with the difference of a pure controlling concept instead of an experimentally supported regulation concept. The first tests of the developed E-BHE with the integrated TRNSYS TYPE 300 model show excellent results for stable running TRT units (timely constant volume flow and thermal power). The measured thermal conductivity by the ZAE TRT unit deviates in first tests only 2.4 % +/-2.2 % in comparison to the default thermal conductivity of the simulation model of the E-BHE. With the first tests the concept of the E-BHE could be validated and also the next steps of development were worked out. In the future, it will be possible to check TRT units in short time steps after each other under reproducible boundary conditions and to optimize them. As an overall effect this leads to an improved calculation of BHE fields and with it to an enhanced dissemination of the geothermal technology.

REFERENCES

[1] S. Gehlin, *Thermal Response Test – Method Development and Evaluation*, Doctoral Thesis, Department of Environmental Engineering, Division of Water Resources Engineering, Lulea University of Technology, Lulea, 2002

[2] Verein Deutscher Ingenieure e.V., *VDI Richtlinie 4640 Blatt 5 Entwurf: Thermische Nutzung des Untergrunds – Thermal Response Test*, Beuth Verlag GmbH, Düsseldorf, 2016

[3] A. Corcoran et al., *Calibration of thermal response test (TRT) units with a virtual borehole*, Geothermics 79 (2019) S. 105-113, 2019

[4] P. E. Nejad et al., *A virtual borehole for thermal response test unit calibration: Test facility and concept development*, IGSHPA Research Track September 18-20, 2018 Proceedings, 2018

[5] A. Busso et al., *Two Applications for Thermal Response Test Data Evaluation – TRNSYS TYPE 300 and TRT Analysis Tool*, Effstock 2009 Proceedings, 2009

[6] A. Huber, O. Schuler, *Berechnungsmodul für Erdwärmesonden*, Schlussbericht, Bundesamt für Energiewirtschaft, 1997

[7] F. R. Calvo, *Analisis y modelado de una instalacion geotermica para climatizacion de un conjunto de oficinas*, Doctoral Thesis, Universitat Politecnica de Valencia, 2015

[8] M. Reuss, *Qualitätssicherung bei Erdwärmesonden und Erdreichkollektoren*, Abschlussbericht, Bundesministerium für Wirtschaft und Technologie, 2012