MODEL-BASED SYSTEM ASSESSMENT OF THERMOELECTRIC ENERGY HARVESTING FROM THE EXHAUST GAS PIPE OF OIL-FIRED HEATINGS

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We present a methodology to assess the design of ther-moelectric Energy Harvesting Systems (EHS) from exhaust gas pipes. In this application, thermoelectric generators (TEGs) are used to generate electricity using a temperature difference, based on the Seebeck Effect. The hot side temperature is given bythe waste heat in theexhaust gasof an oil-fired heating system and, at the cold TEG side, two different cooling options are considered, forced air and liquid cooling. The assessment is based on a comprehensive modular model, which includes, besides a detailed TEG model, the heat transfer conditions as well as an adaptive control strategy.The model, build up in the modeling and simulation environment Modelica®/Dymola®, serves to design such an EHS in an optimal way, meaning that a reasonable number of TEGs for the system and a suitable cooling method are chosen.Moreover, for each cooling method, an individual control strategy is defined to maximize the power output of the EHS.

KEYWORDS
thermoelectric generator,oil-fired heating, energy harvesting, system assessment, Modelica®

1. INTRODUCTION

1.1 Energy Harvesting Systems

Energy Harvesting Systems (EHS) shall produce a small amount of electrical energy. This can be done with the help of thermal, kinetic, wind or solar energy, whereby always different physical effects are used. The gained energy from the EHS supplies usually low power devices, e.g. wireless devices and is buffered in a battery [Priya 2008]. In general, EHSs use waste energy sources, i.e., though they produce only a small amount of electrical energy with rather low efficient, they are useful and can help contribute to a better exploitation of the primary energy carrier. A further advantage of EHSs is the energy production and consumption on the spot. This means, there is no need for external energy supply via long cable lines or batteries, which have to be replaced after a certain period of time. In industry, for example, this fact can be used for sensors which are located in hard-to-reach places. In this paper, a thermoelectric EHS is considered. This system consists of thermoelectric generators (TEGs), which use the Seebeck effect to generate electrical energy from a temperature difference (cf. Sect. 1.2).

A lot of research was done in the last decades and is still ongoing in the area of waste heat recovery, because there are so many combustion processes, in the industry as well as in common households. For all of this waste heat processes, there is a considerable potential of efficiency enhancement. One exemplary application is to use the heat of the exhaust gas line in automobiles with TEG-based EHSs, see [Anatychuk 2012, Hsu 2011]. Another application is a more efficient use of solar energy; in addition to the visible light, [Date 2014] use the infrared sunlight. As more than half of the energy coming from the sun is thermal energy, this seems reasonable. Other researchers consider thermoelectric EHSs in combination with phase change materials, see [Elefsiniotis 2013, Kiziroglou 2014]. In [Zhu 2011], an experimental study of a thermoelectric generation system for application in exhaust heat of kilns is developed.

In the current work, a ordinary oil-fired household heating system is considered. The EHS based on TEGs is attached to the exhaust gas pipe. In almost every German household a heating system is installed and so there is a big potential for EHS – all the more considering that 91.6 % of heating energy used in Germany (2010) comes from fossil sources, and estimated 77 % of those heating systems have inadequate efficiencies [BDH 2011]. The gained energy could be used for a variety of DC home applications. Moreover, it may supply the heating controller; so the heating system will be autarkical and operational during a blackout as well. The exhaust pipe of the heating system is representative for other possible exhaust pipes, e.g. in industry or in automobiles.

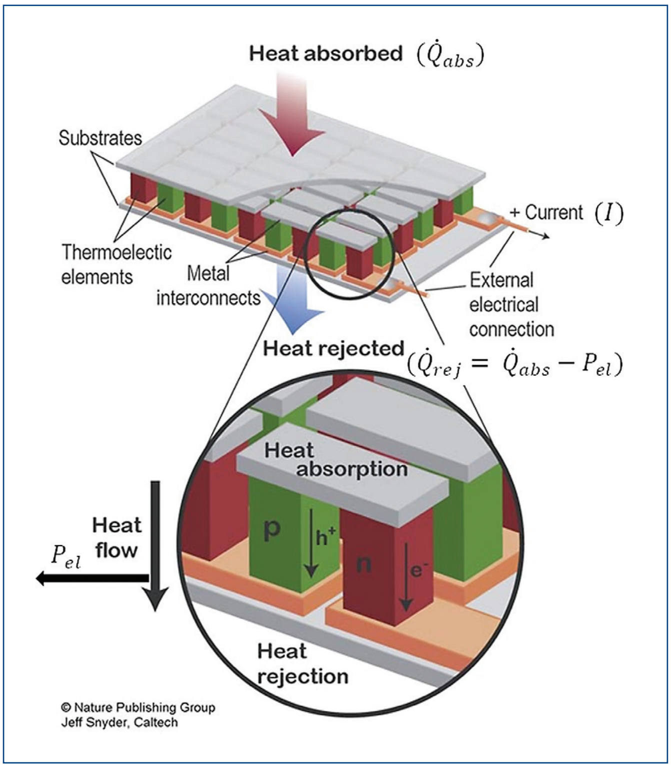

Figure 1. Structure of a thermoelectric device with heat flows in steady-state, enlarged is one thermocouple; adapted from [Snyder et al 2008].

1.2 Basics of TEGs

TEGs are devices producing electrical energy from heat. They consist of thermoelectric material, which generates electrical energy due to a temperature difference. A thermoelectric device is represented in Fig. 1. It consists of a multitude of thermocouples, which for their part consist of two legs – n- and p-doped (e.g. Bi_2Te_3, PbTe, SiGe) – linked by a metal bridge. Their outer endings are ceramic plates. Applying a temperature gradient over the thermoelectric device causes different physical effects, whereat the resulting electromotive force (EMF), called Seebeck effect, is the crucial one to generate electricity. In addition to that, also a use case in the reverse case is possible. The advantages of TE devices are the simple scalability, their high reliability and their low amount of maintenance required, owing to the lack of any moving parts or working fluids. Their disadvantage is the low efficiency and their high costs. The TEGs only reach a maximum efficiency of more or less 5 %. In steady-state, it is calculated according to (1), with being the produced power and the heat absorbed on the hot side, [Goldsmid 2010].

$$\eta = \frac{P_{el}}{\dot{Q}_{abs}}, \quad (1)$$

$$P_{el} = I^2 R_L = \left(\frac{(\alpha_p - \alpha_n)(T_h - T_c)}{R_p + R_n + R_L}\right)^2 R_L, \quad (2)$$

$$\dot{Q}_{abs} = (\alpha_p - \alpha_n) I T_h + (K_p + K_n)(T_h - T_c), \quad (3)$$

where is the current [A], the electrical resistance [Ω], α the Seebeck coefficient [V/K], T the Temperature [K] and K the thermal conductance [W/K]. The indexes p and n represent the p- and n-doped thermolegs, L the load and and the hot- and cold-side TEG temperatures. The low efficiency makes it all the more important to build up a well-tuned EHS to harvest as much energy from the system as possible. This applies to the effectiveness of the EHS itself and to the maximal extracting of heat from the exhaust gas pipe. This paper deals with the EHS itself. To design a well-tuned EHS based on TEGs, a modular simulation model has been composed for this work.

The EHS as well as the heating system considered in this paper are modeled in the object-oriented modeling language Modelica® [Modelica 2015]. It allows the modeling of complex physical systems with component-oriented concept. For editing and simulation, Dymola® Version 2014 was used.

1.3 Contribution and Organization of the Paper

Here, the purpose of the modeling and simulation is the thermo-electric EHS assessment and improvement during the design phase. Consequently, Sect. 2 deals with the system modeling of the EHS in Modelica®/Dymola®. First, it describes the construction of a real EHS, attached to the exhaust gas pipe of an oil-fired heating, and then the transfer of the real conditions to the model level. In Sect. 3, different control concepts are presented concerning the TEGs (Subsect. 3.1) as well as the different cooling methods (Subsect. 3.2). The in this paper applied control laws are introduced in Subsect. 3.3. In Sect. 4, the model-based system assessment of an EHS is described. Subsect. 4.1 deals with the assessment of the cooling methods and Subsect. 4.2 with the suitable number of TEGs. Finally, Sect. 5 provides conclusions.

2. SYSTEM DESCRIPTION AND MODELING

Here, the EHS consists of eight TEGs and is attached to the exhaust gas pipe of an oil-fired heating system. Eight TEGs are installed pairwise, with both TEGs of each pair subject to identical temperature conditions. In the end, there are four pairs of TEGs (pTEGs) operating under different temperature conditions. Fig. 2 shows an example of such a system. It shows the first possible cooling principle, cooling by liquid, whereat one cooling unit supplies two pTEGs; later, this fact will be of importance. The liquid cooling units only have one state and consume 12.2 W with a maximal cooling capability of 400 W. The reason for this lies in the condition of using simply disposable cooling elements, due to the objective of modifying existing heating systems in a very simple and economic way. Considering that one liquid cooling unit is responsible for four TEGs, one TEG consumes 3.05 W of electrical power for cooling purposes. Electrically, the TEGs of one pTEG are connected in parallel, while the four pTEGs are connected in series. For the control (cf. Sect. 3), there are electrical bypasses between the pTEGs to disconnect or connect specific pTEGs.

For the modeling of a TEG itself, there exists a 'Thermoelectric-Generator' library in Modelica®, which has first been outlined in [Felgner 2012], refined in [Felgner 2014], and extended in [Nesarajah 2014a]. It is a component-oriented model of a TEG, which includes the temperature dependences of material properties (Seebeck coefficient, thermal conductivity, and electrical resistivity) in a 1D spatial resolution. With this approach the model can describe the dynamic behavior of TEGs. Here, TEG 199-200-5 from Thermalforce is used and the graphical user interface of the TEG model has to be fed with data of the TEG datasheet, [Thermalforce 2015].

Further components are modeled with components from the Modelica® Standard Library, in this instance from the Fluid, Thermal and Electrical libraries [Modelica 2015]. The exhaust pipe is modeled by using the 'DynamicPipe' component, which provides the equations for the exhaust gas flow inside the pipe as well as the heat transfer through the sheath. It is also used for modeling the liquid cooling system pipes, where water is used as cooling medium for modeling simplification. Measurement data of the real oil-fired heating deliver the necessary information to model the heating component and to simulate real behavior of the exhaust gas. For maximum power output of the EHS, a maximum power point tracker (MPPT) is necessary to adapt the internal resistance of the system to the load. For that reason, an ideal MPPT model component is created, which gets the values of the internal resistances of the TEGs from the TEG-components itself and thus calculates the optimal load resistance for the circuit.

The energy consumption and generation of the components is integrated inside each model and the component 'power supply' serves as battery for the liquid cooling system. In addition to it, the main system calculates directly the complete produced electrical energy and the real gained energy (= produced energy by pTEGs minus energy consumption of the cooling components).

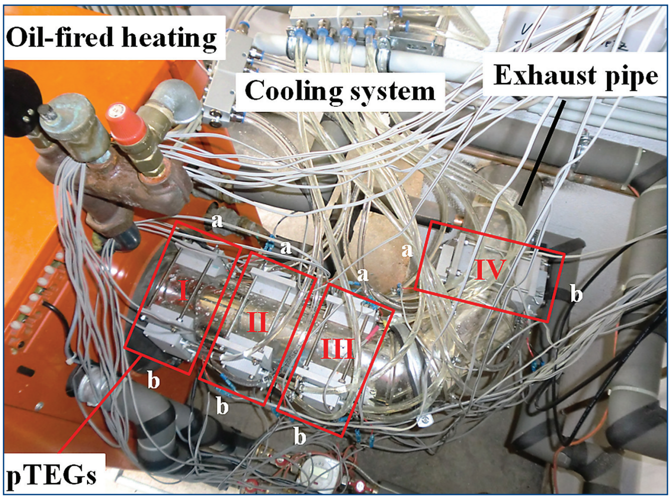

Figure 2. Test bench on an exhaust pipe of an oil-fired heating system consisting of four pTEGs (marked with roman numerals), each includes two TEGs (marked with 'a' and 'b') and a liquid cooling system.

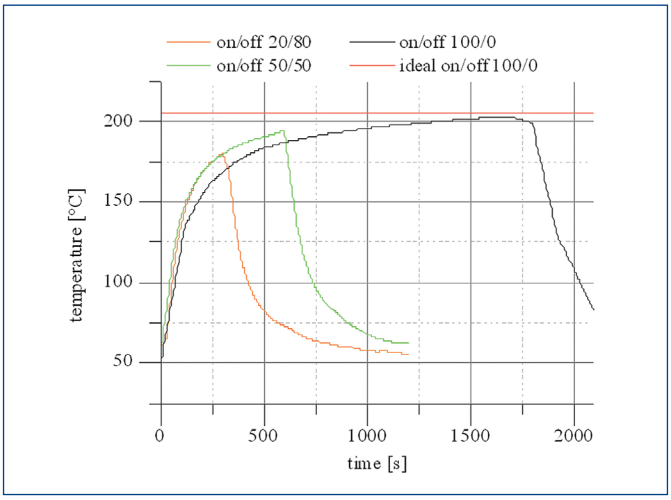

Figure 3. The three real measured temperature curves (black, green and orange) as well as the upper limit temperature line for the ideal steady-state full-load operation mode (red)

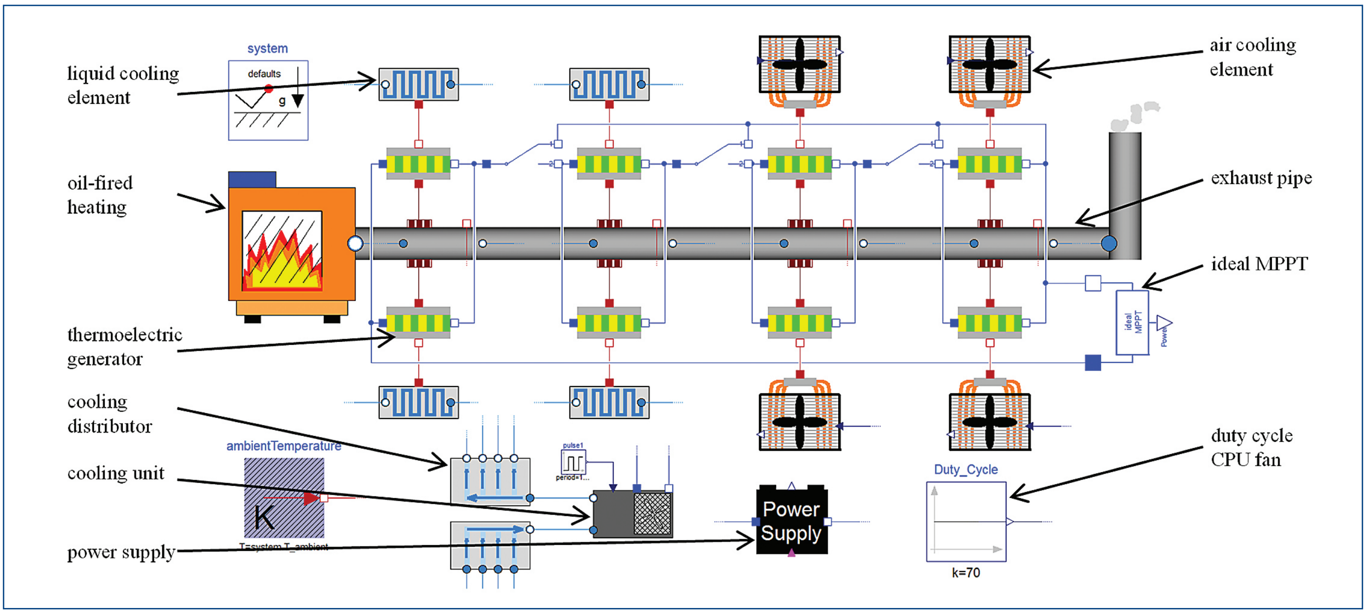

Figure 4. Model of the EHS in Modelica®/Dymola® showing the different components and in particular the different cooling options. The electrical wiring is represented by the navy blue lines.

In general, the temperature of the heating exhaust gas fluctuates between 120 and 200 °C [Paschotta 2015, Möbus 2015, Nowotka 2003]. Fig. 3 shows a real measurement curve (black) of an oil-fired heating under full-load operation over a period of 2.100 s. It is visible, that the final temperature is about 205 °C for this special heating scenario. So it is obvious, that this heating is an older one and not really efficient. Moreover Fig. 3 shows two further measurement curves for an on/off behavior (50 % on and 50 % off as well as 20 % on and 80 % off) of the heating and one fictitious ideal steady state curve for full-load operation based on the upper bound of the real measured exhaust gas temperature curve. In the following, the three colored curves in Fig. 3 serve as simulation inputs and are representative for three different heating loads. In the end, two different heating modes, full-load operation and on/off behavior are considered, whereby the latter one is split up in two scenarios with a ratio of 50/50 and 20/80. The full-load operation mode can be considered as an on/off ratio of 100/0. The curves have been recorded in the 'oil-fired heating' component.

Fig. 4 shows the complete system model in Dymola® and highlights the different components. To illustrate all possible cooling options, the first two pTEGs are water cooled and the last two pTEGs are air cooled (only for illustration, later, there is either a pure water cooling or a pure air cooling). The electrical wiring and in particular the bypasses for the eventual control of the system are visible, whereas, for a better overview, the other connection lines like fluid and thermal connections are hidden.

All results in the following sections are simulation results of the modeled TEGs and cooling elements. However, the temperature curves of the exhaust gas are measurements.

3. CONTROL CONCEPT

3.1 Connection/Disconnection of pTEGs

The core idea of removing (disconnecting) and reviving (connecting) single TEGs to increase the power output of an EHS, originates from the work of M. Chen, cf. [Chen 2014]. He suggests removing and reviving TEGs, depending on the overall electrical energy output of the EHS, and assumes that there are single TEGs subject to completely different temperatures at different places in the system. Therefore, the optimal wiring for each operating point is computed with a co-simulation between LabView® and Multisim®. In some cases, due to the internal resistance of each single TEG, it makes more sense to disconnect detrimental TEGs or to reconnect them. This is understandable by regarding an equivalent circuit diagram of a TEG, see Fig. 5. It is an EMF (voltage source) in series with a resistance (the internal resistance of the TEG) and if the power loss across the internal resistance is too high, the TEG delivers no contribution to the performance of the system.

The most obvious layout of a TEG-based EHS is to install pTEGs alongside a pipe (in contrast to Chen). With the exhaust gas losing heat in downstream direction, the final pTEGs are expected to provide the least contribution to the EHS output. Even worse, those underperforming pTEGs may lower the EHS performance, due to their internal electrical resistance, their low thermoelectric voltage and the energy consumption of their cooling device. The electrical wiring is obvious in Fig. 4 (navy blue lines), and by contrast to Chen, complete pTEGs can be disconnected and reconnected as both TEGs of the same pTEG are subject to the same temperature conditions.

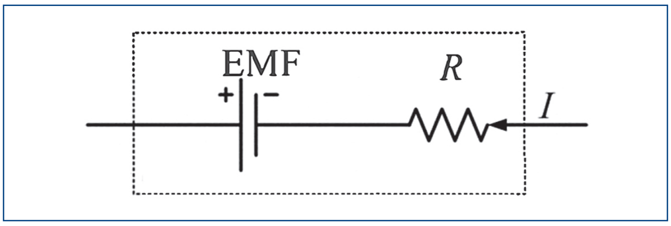

Figure 5. Equivalent circuit diagram of a TEG, [Chen et al. 2011].

However, as shown in [Nesarajah 2014b], there is no reason to disconnect any pTEG in that setup, concerning the internal resistance. Admittedly, the power output of the last pTEG is reduced, but anyway, it is still a positive contribution to the EHS. So, there is no negative influence based on the internal resistance of the TEG. For that reason, now, the cooling and its energy consumption have to be taken into account.

3.2 Cooling Control

3.2.1 air cooling

For the forced air cooling of the TEGs, high-end CPU cooling elements known from computer applications are used, [Scythe 2015]. The CPU cooling element has a heat spreader which is directly contacted with the cold side surface of a TEG. From this heat spreader, heat pipes transferring the heat to a multitude of cooling fins, which are cooled down by a controllable fan. The energy consumption of the air cooling devices is shown in Fig. 6 as well as the possible fan speeds. They are adjustable by their duty cycle. The air cooling method uses only 2.04 W in case of maximum fan speed and normally even less for one TEG. The data of the CPU cooling element datasheet, see [Scythe 2014], have been used to create a simulation model (c.f. Fig. 4). To validate this model, the measurement data of a test set-up are compared with the corresponding simulation results, which have provided a very good match.

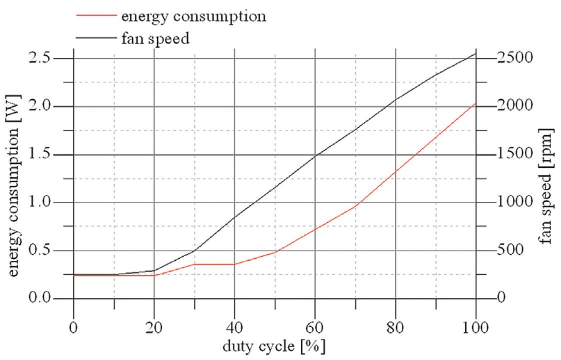

Figure 6. Energy consumption by fan and fan speed of air cooling elements for different duty cycles, required for modeling,[Scythe 2014].

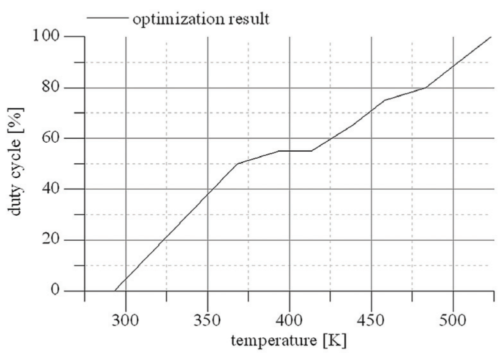

Figure 7. Control curve for the duty cycle of the cooling elements depending on the hot side temperature of a TEG.

The simplest way of running the fans is with a constant rotating velocity, set up by their duty cycle. But to increase the efficiency, a control of the fan speed has been developed with the help of the 'Optimization' library of Dymola®. Thereby, the optimal duty cycle and, as a consequence, the optimal fan speed is assigned to the hot side temperature of the considered TEG, see Fig. 7. The fan speed control adapts the energy consumption in an optimal rate to the produced power of the pTEGs.

3.2.2 liquid cooling

As mentioned in Sect. 2, the available liquid cooling units have only one state and consume 12.2 W. Consequently, here is no control like with the air cooling possible. The control strategy, which is used for the liquid cooled system is to switch off/on a cooling unit, whenever the produced power of the pTEGs, which are cooled down by the unit, is less/more than the energy consumption of the cooling unit itself.

3.3 Control Laws

Control concepts are explained in Sect. 3.1 and Sect. 3.2. Now, they are verbalized into the following control laws (CLs); they are opposed to the uncontrolled reference system, identified by CL0:

CL0: The cooling units run all the time. There is no control strategy applied neither for the air cooled nor for the liquid cooled system.

CL1: Switch off the complete EHS as soon as the pTEGs produce less than the cooling elements consume.

CL2-L: Disconnect/connect a set of pTEGs (and the corresponding liquid cooling system) whenever the produced power is less/more than the sum of the power used for its cooling and the power loss due to its internal electrical resistance (cf. Subsect. 3.1. and 3.2.2).

CL2-A: The air cooling elements are controlled like described in Subsect. 3.2.1.

CL0 and CL1 refer to both cooling methods, whereby CL0 for the air cooled system means, that the duty cycle of the fan speed is 100 % and for the liquid cooled system, that the units are on all over the time. The CL2 is divided in one law for the liquid cooled (–L) and one for the air cooled system (–A). As described in [Nesarajah 2014b], the removing and reviving concept delivers no advantage for the air cooled system, due to the fine control of the fan speed.

In the following, a uncontrolled EHS means CL0 and a controlled EHS the usage of CL1 and CL2-L/CL2-A.

4. MODEL-BASED SYSTEM ASSESSMENT

To assess a conceived EHS construction, a simulation model as mentioned in Sect. 2 is required. With the system model, the exhaust gas pipe of a heating, the thermoelectric elements as well as the two different cooling options are emulated. To evaluate the design and to optimize the construction for an EHS at a special heating, only the normal temperature curve of the exhaust gas at the real system is necessary. Given these measurement data, the simulation will enable the detection of the optimal number of pTEGs as well as the suitable cooling method.

cooling method	control concept	gained power
air cooling	uncontrolled	30,7 W
	controlled	34,1 W
liquid cooling	uncontrolled	34,7 W
	controlled	34,7 W

Table 1. The finally gained power for both cooling methods and their different control concepts for the steady-state temperature (100/0 on/off behavior) (red line in Fig. 3). The uncontrolled and controlled liquid cooling are identical in that case.

4.1 Cooling methods

There are two different cooling methods to cool down the cold side of the TEGs. One is the cooling with a liquid cooled system and the other is cooling by forced air. Moreover, there is a different control strategy for each cooling method, which was explained in Subsect. 3.2.

The following figures show respectively one of the three heating behaviors as presented in Fig. 3. Tab. 1 shows, corresponding to a steady-state scenario, the full load operation mode (100/0). In this scenario, it is obvious, that liquid cooling is more effective than air cooling and in air cooling scenarios, the controlled case is better than the uncontrolled one (for liquid cooling, they are identical).

Fig. 8 and Fig. 9 show the power gained for the different cooling methods in an on/off behavior of the heating. Fig. 8 shows the 50/50 and Fig. 9 the 20/80 ratio. In both cases, the advantage is with the controlled air cooling system and of course, in both cases, the controlled case is better than the uncontrolled.

Furthermore, the different control laws, mentioned in Sect. 3.3, are visible. The uncontrolled curves represent CL0. If we consider e.g. the controlled liquid curve (blue line) in Fig. 8, CL1 keeps the system on

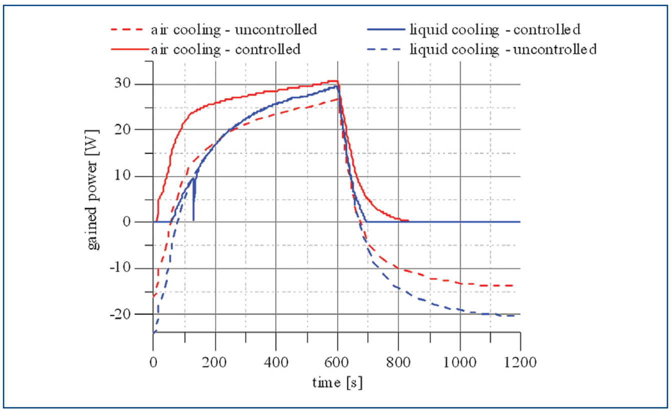

Figure 8. The finally gained power for both cooling methods and their different control concepts for the 50/50 on/off behavior (green line in Fig. 3).

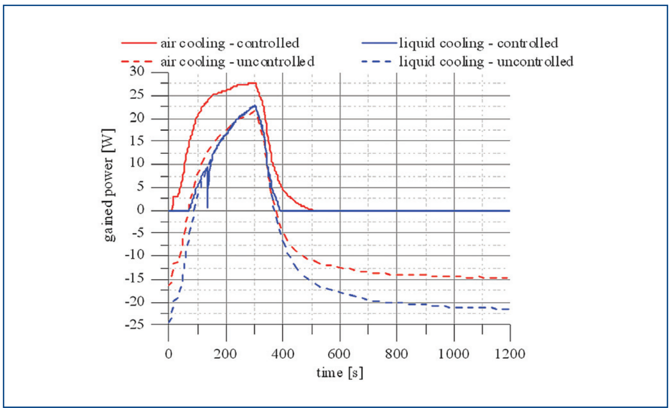

Figure 9. The finally gained power for both cooling methods and their different control concepts for the 20/80 on/off behavior (orange line in Fig. 3).

zero (compare the beginning and the end of the curve). The peak at approx. 125 s is based on CL2-L. It is the moment, when pTEG3 and pTEG4 (cf. Fig. 2) are connected as well as their corresponding cooling unit is switched on. Primarily, the cooling consumes more energy until the cooling effect of the cooling systems occurs.

As a result of the assessment with different heating loads, it can be noted that, for a high constant temperature, the liquid cooling is preferable and for the other cases, on/off behavior far away from 100/0, the air cooling is preferable. The reason for this lies in the more flexible control of air cooling elements during transient phases, which was discussed in Subsect. 3.2.1. A summary of the efficiency of the different cooling methods and their control for different heating loads is given in Sect. 5.

4.2 Finding the optimal number of pTEGs

The number of pTEGs can also be determined with the help of the developed simulation model applied in this paper. If only the controlled cooling systems are considered, a further pTEG does not lower the output of the EHS. If it would, the control strategy would shut off the cooling and disconnect the pTEG from the system, cf. Subsect. 3.3. The remaining question consequently concerns the economy. Theoretically, a large amount of pTEGs can be attached to an exhaust gas pipe, although the last pTEGs are only connected with the system very rarely or never in the worst case (due to the applied control laws). The choice consists in determining the optimal number of pTEGs installed in the system. Therefore, the delivered extra energy of the additionally added pTEG has to be compared with the investment costs and based on that, a reasonable number of pTEGs has to be determined.

5. CONCLUSIONS

To design a thermoelectric energy harvesting system in an optimal way, the use of a simulation model is strongly recommended. Common household oil-fired heatings have an exhaust gas temperature between 120 and 200 °C. Depending on the maximum reached temperature and the temperature curve itself, an economic and reasonable EHS has to be built up. With the simulation model applied in this paper, the number of pairs of thermoelectric generators (pTEGs), the suitable cooling method and the control strategy can be determined. For this purpose, only representative curves of the exhaust gas temperature of the real oil-fired heating are necessary.

In addition to the model-based assessment of an EHS conceived, two generic control laws were formulated and applied. They refer to dynamic changes in the topology of the electric circuit of connected/disconnected pTEGs as well as to the respective cooling method applied. One concerns the air cooling and the other one the liquid cooling system.

The crucial results are summarized in Table 2. They shall give practical advice concerning an appropriate TEG-based EHS depending on the boiler control on/off ratio, which is representative of the heating system considered for energy harvesting. The red arrays (-) are very bad solutions, this means they deliver a negative energy output after the simulation time and as a result they must be avoided. The orange (+) and green (++) arrays show solutions, which generate a positive energy output after the simulation time, whereby the green array shows respectively the best solution for the special heating load scenario. As shown in the table, there are scenarios, where a liquid cooled EHS is advantageous. This will be especially the case for heatings run under full-load operation, meaning a steady state behavior. For on/off scenarios (dynamic behaviors) the advantage is with the air-cooled EHS.

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cooling method	control strategy	on/off ratio of boiler control		
		100/0 Fig. 7	50/50 Fig. 8	20/80 Fig. 9
air cooling	uncontrolled (CL0)	+	–	–
	controlled (CL1 + CL2-A)	+	++	++
Liquid cooling	uncontrolled (CL0)	++	–	–
	controlled(CL1 + CL2-L)	++	+	+

Table 2. Overview for different heating load scenarios; red arrays (–) deliver a negative energy output, orange (+) and green (++) arrays positive energy outputs, whereas the green arrays deliver the highest output for a certain heating load scenario.

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