Comparability of the cooling effect of Peltier thermoelectric elements in a chemiluminescence analyzer under extreme climatic conditions

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***Abstract*— In this work, the comparability of the cooling effect of two Peltier elements from different manufacturers is investigated for cooling the reagent module of a chemiluminescence analyzer. The temperature inside the reagent module is measured and evaluated at several positions. In this study, two different types of verification tests are performed under extreme climatic conditions. On the one hand, in a specific functional "cold start test", the temperature in the reagent module is measured and evaluated to determine whether the measured temperatures are within the specified temperature range after the specified time. In addition, the performance of the Peltier elements is also evaluated. On the other hand, as an unspecific regression stress test, a "smoke test" is performed that is mainly designed to allow identifying unpredictable events. While processing a long and complex work list, any deviant system behavior can be detected. Again, the temperature inside the reagent module should not exceed the specified temperature range.**

I. Introduction

The thermoelectric cooling effect of a Peltier element is based on the inversion of the Seebeck effect, which is caused by the different Fermi levels of the connected metals. The Seebeck voltage only occurs if a temperature change causes the Fermi level to shift differently for the two bonded metals [1] [2]. Peltier elements consist of two semiconductors, P-type and N-type, and connecting bridges [1]. Depending on the direction of the current, one contact point heats up by releasing energy, while the other contact point cools down by absorbing energy. This effect is based on the decrease of charge carriers in the coupling bridge on the cold side, which leads to a decrease of the thermoelectric voltage between the bridge and the semiconductors [1]. In this work, Peltier elements are used to cool the reagents in the [redacted] chemiluminescence analyzer. Due to supply shortages of the currently used Peltier elements from [redacted], alternative parts from another supplier, [redacted], have to be qualified [3]. Therefore, the interchangeability of the Peltier elements is investigated within the scope of this work by means of verification tests.

In addition to measurement and evaluation, the chemiluminescence analyzer also handles complete sample processing. [redacted] [4]. The required reagents are provided in a reagent module. The reagent module consists of 25 reagent lanes into which reagent integrals are inserted. Each integral contains several vials with the complete set of reagents required for one assay. Furthermore, up to four individual reagents (ancillaries) can be placed in an additional lane on the left side of the reagent module. This allows multiple assays to be performed simultaneously. To ensure adequate cooling of the reagents, Peltier elements are installed in the reagent module. The Peltier elements are sandwiched in between a warm side heat sink and an adapter block with a graphite foil layer in between each of the mentioned components for better contact, which results in better heat transfer. The cold side of the Peltier elements consists of aluminum cooling fins so that the reagents can be inserted directly between these cooling fins. The reagent module includes three Peltier assemblies that are controlled individually. Each assembly contains two Peltier elements. In fact, the main difference between the two suppliers' Peltier elements is the smaller thickness of the alternative elements. This is compensated by an extension of the adapter block. The temperature control is maintained without firmware changes and is expected to be without effect on cooling behavior in regular environmental conditions. The elements' thermoelectric specifications are in a tight comparable range. Theoretically, an increase of power consumption of approx. 4 % can be assumed when using the alternative Peltier elements, as shown in the data sheets [3]. Since the replacement of the Peltier elements could affect the performance requirements or other quality characteristics, the verification tests of the Peltier elements are performed at system level under extreme climatic conditions. The tests focus on the most disadvantageous conditions for the cooling process at the upper limit of the operating range at a temperature of T = 32 °C and a humidity of rH = 85 %. [3].

II. Materials and Methods

A. Materials and measuring devices

This section describes the materials and measurement equipment used in this work. Table 1 provides an overview of the materials and equipment and the measurement uncertainties of the used devices.

Table 1: Materials and equipment used in this work with indication of the measurement uncertainties at extreme conditions.

Device	Manufacturer	Type	Accuracy
Datalogger	Graphtec	GL240-EU	± 0.5 °C
Climatic data logger	Testo SE & Co. KGaA	Testo 184 H1	± 0.5 °C ± 4.35 %rH
Thermocouple (Temperature sensor)	RS Components (RS Pro)	K	± 1.5 °C
Water cooled refrigerated thermostat	LAUDA	ECO RE630	-
Reference thermometer	Ludwig Schneider GmbH & Co. KG	Physics 1000-R1	± 0.015 °C
Chemiluminescence Analyser	STRATEC SE	[redacted]	-
Climate chamber	Frank Schlittenhardt GmbH	Special design	-
Current Peltier elements	[redacted]	[redacted] Confidential	-
Alternative Peltier elements	[redacted]	[redacted] Confidential	-

B. Temperature sensor calibration

Due to the measurement accuracy of the data logger and the temperature sensors used (see Table 1), a summarized accuracy of ± 2.0 °C is calculated. To enhance the accuracy of the measurement, all sensors are calibrated against the reference thermometer in a conditioned water bath (LAUDA ECO RE360) along the complete temperature range in connection with the data logger. All sensors have a fixed relation to the data loggers measuring channels. The achieved total accuracy is expected to be at most about one order of magnitude better than the calculated accuracy without any calibration. Thus, the measurement accuracy for the used data logger with each sensor and channel calibrated in water bath against reference thermometer is estimated to be at least between ± 0.2 °C and ± 2 °C or better [5].

C. Measurement Setup

Based on previous qualification tests, the chemiluminescence analyzer is subjected to a "cold start test" and a "smoke test" [6]. To obtain comparable data regarding the current and alternative Peltier elements, the climate chamber tests are first carried out with an [redacted] instrument equipped with the current Peltier elements. Subsequently, the verification tests are performed with a reagent module equipped with the alternative Peltier elements, installed in the otherwise unmodified [redacted] instrument. During the test execution, all covers are installed and all flaps are closed to simulate a real laboratory environment. To ensure stable climatic conditions, the climate chamber is set to the target temperature and humidity at least four hours before the start of the test. With the aim to simulate conditions in field, the integrals and ancillaries are prepared and precooled in a refrigerator for at least four hours. In this work, verification is performed with DI-Water instead of chemical reagents. The integrals and ancillaries are removed from the refrigerator only shortly before the start of the verification tests. The temperature is measured at different positions (see Table 2) [5].

Table 2: Assignment of the measuring position to the channels of the data logger.

No.	Measuring position in the chemiluminescence analyzer	Data logger channel
1	Ancillary in rearmost position	CH3
2	Ancillary in foremost position	CH4
3	Integral lane 1, rear vial (L1, rear)	CH5
4	Integral lane 1, front vial (L1, front)	CH6
5	Integral lane 13, center vial (L13, center)	CH7
6	Integral lane 25, rear vial (L25, rear)	CH9
7	Integral lane 25, front vial (L25, front)	CH10

The temperature sensors are fixed in the unit at the corresponding measuring points with the help of aluminum tape. It is ensured that the cables of the temperature sensors do not come into conflict with the pipettor [6].

In addition to the temperature measurement at the corresponding measuring position, the power required by the alternative Peltier elements to achieve a comparable cooling effect to the currently used ones is also considered.

D. Measurement procedure

The current and alternative Peltier elements are tested comparatively under the same conditions. To investigate the comparability of the cooling performance, three "cold start tests" and one "smoke test" are performed with the actual and the alternative Peltier elements each. The measurement procedure of these verification tests are described below. Both tests are performed under extreme climatic conditions at an ambient temperature of $T = 32$ °C and a humidity of $rH = 85$ %, which corresponds to the upper limits of the operational range [6].

<u>"Cold Start Test"</u>

The "cold start test" is a specific functional verification test against specified temperature and time targets, starting with the instrument switched off and acclimatized for at least four hours. Thus, after the temperature sensors have been properly placed (see Table 2), the temperature data logger is switched on first. Subsequently, the precooled ancillaries and integrals are inserted into the corresponding positions in the reagent module. Next, the temperature sensors must be immersed into the corresponding ancillary and integral liquid vials. When all preparatory steps have been completed, the chemiluminescence analyzer is switched on. At this point, the reagent module starts cooling immediately. Then the service software (SSW) is started and the complete system is initialized. To prevent the temperature sensors from slipping out of the assay vials, the reagent stirrer is switched off during the test. Using a mouse macro recorder, the internal temperature values of the system are written to a SSW log file, which is available for the evaluation of the test. The target temperature of $T = 13 \pm 2$ °C shall be reached within $t = 60$ min, as specified. Furthermore, the measured values are evaluated after $t = 90$ min [6].

<u>"Smoke Test"</u>

The goal of the "smoke test" is to perform a long and complex work list to identify any unforeseen difficulties. The smoke test starts with the instrument at operating state temperature and focuses on climate-related error messages. The ancillaries and the integrals in which the temperatures are measured are placed in the same positions as in the "cold start test". The integrals needed to perform the assays of the "smoke test" are placed in the remaining integral lanes. The "smoke test" is performed with six different assays, each sample with six replicates. This corresponds to 288 jobs to be performed. After the chemiluminescence analyzer is initialized, a selection of samples is assigned to different assays. In principle, 120 different samples should be used. At least 240 jobs must be processed successfully. After the extensive assay work order has been started, it is necessary to wait until the test run has been completed. Afterwards, the number of successfully executed jobs (at least 240) is checked. During the test, attention must be paid to determine if error messages appear during the test run. [6].

III. RESULTS AND DISCUSSION

A. Environmental conditions

The ambient temperature reached in the climatic chamber during the tests had been between 32.00 °C $\geq T \geq$ 32.40 °C and the humidity achieved a value between 84.99 % $\geq rH \geq$ 87.38 %.

B. "Cold Start Test"

In this section, the "cold start tests" of the current and alternative Peltier elements are evaluated. For reasons of clarity, only the measured data of the channels CH3, CH4 and CH7 are shown graphically.

<u>Current Peltier elements</u>

Figure 1 shows the characteristic shape of a "cold start test" of the currently used Peltier elements. The origin indicates the time when the laboratory analysis system is switched on. At this point, the Peltier elements start cooling immediately. The graph shows that the precooled integrals and ancillaries are initially heated by the extreme conditions in the climatic chamber.

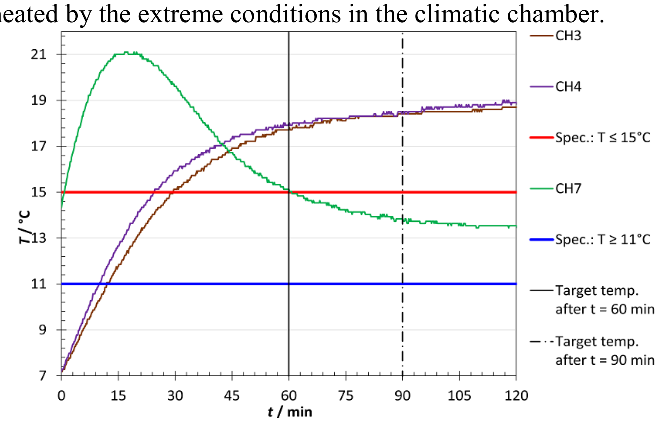

Figure 1: Characteristic shape of a "cold start test" of the currently used Peltier elements.

The ancillaries have a larger filling volume than the integrals, which is why they have a greater heat capacity and are warmed up more slowly by the ambient temperature than the integrals (see Figure 1). On account of the low heat capacity, the integrals initially show a parabolic characteristic before the temperature converges asymptotically to the target temperature range. Compliance with the specified temperature range of $11\ °C \leq T \leq 15\ °C$ is just met as required after $t = 60$ min for the measurement position CH7. The ancillaries do not meet this requirement. The integrals are efficiently cooled by the aluminum fins of the Peltier elements due to their good thermal conductivity. The ancillaries are separated from the integrals by a partition wall made of aluminum and a storage drawer made of aluminum and plastic. The higher temperature in the ancillaries of approx. $T \approx 20.5\ °C$ is accepted for the further process, which is why the measured values can be used as a reference for testing the alternative Peltier elements [6]. It should be noted that the temperature in the ancillaries has not yet reached a stable state due to the short measurement period. Based on an overnight measurement, an approximation to $T \approx 20.5\ °C$ can be expected. In the following, only the measured temperature values of the integrals are evaluated.

Table 3 documents the time required to reach the specified temperature range for each measurement position in the integrals of the currently used Peltier elements.

Table 3: Calculation of the mean value for each measurement position of the current Peltier elements. The target temperature should be reached within t = 60 min. (green = specification met; gray = specification not met).

Test No.	Time required to achieve the specification t [min]				
	CH5	**CH6**	**CH7**	**CH9**	**CH10**
1	89.6	51.8	60.8	49.4	81.3
2	91.7	43.5	55.8	45.8	73.8
3	103.7	47.5	58.3	45.8	75.0
$\bar{x}$	95.0	47.6	58.3	47.0	76.7

Table 3 shows that the specification of reaching the target temperature of $11\ °C \leq T \leq 15\ °C$, considering the mean value $\bar{x}$, can be met for a total of three measurement positions within $t = 60$ min.

Alternative Peltier elements

Table 4 documents the time required to reach the specified temperature range for each measurement position in the integrals of the alternative Peltier elements.

Table 4: Calculation of the mean value for each measurement position of the alternative Peltier elements. The target temperature should be reached within t = 60 min. (green = specification met; gray = specification not met).

Test No.	Time required to achieve the specification t [min]				
	CH5	**CH6**	**CH7**	**CH9**	**CH10**
1	107.5	57.0	63.0	52.0	91.8
2	129.4	54.6	63.6	52.1	96.9
3	103.3	55.0	64.3	51.5	90.1
$\bar{x}$	113.4	55.5	63.6	51.9	92.9

Compared to the currently used Peltier elements (see Table 3), the alternative Peltier elements require more time to achieve the specified temperature range (see Table 4). On average, the specification is only met for two measurement positions.

Comparison of performances

Figure 2 shows the characteristic shape of the effective duty factor for the left, middle and right Peltier assemblies of the reagent module. To demonstrate the performance of the Peltier elements, Figure 2 shows the effective duty factor for a "cold start test" with the current Peltier elements.

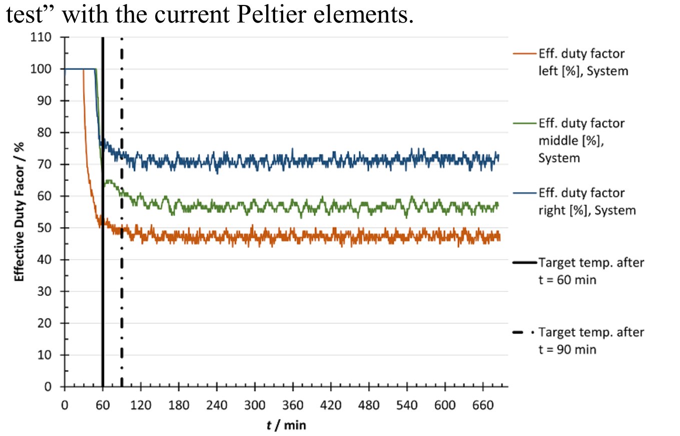

Figure 2: Power performance of the currently used Peltier elements during the "cold start test".

The origin indicates the time when the chemiluminescence analyzer is switched on. At the beginning, the Peltier elements are cooling the reagent module with a power of 100 %. For the left-hand assembly, the power decreases continuously after $t = 30$ min, for the middle assembly after $t = 50$ min and for the right-hand assembly after $t = 48$ min until the required power stabilizes in a steady state (see Figure 2). Table 5 provides a performance comparison between the current and alternative Peltier Elements. The assembly on the left side of the Peltier Element requires less power than the middle and the right assembly.

Table 5: Performance comparison of current and alternative Peltier elements.

Test No.	Current Peltier elements			Alternative Peltier elements		
	Left	**Middle**	**Right**	**Left**	**Middle**	**Right**
1	47.2	56.6	71.1	51.6	60.6	74.6
2	47.1	55.8	70.8	54.2	68.3	79.6
3	47.3	56.2	71.0	53.3	65.0	77.5
$\bar{x}$	47.2	56.2	71.0	53.0	64.6	77.2

	Left	**Middle**	**Right**
$\Delta\bar{x}$	+ 5.8	+ 8.4	+ 6.2

The alternative Peltier elements require higher power than the currently used Peltier elements at all measuring positions of the reagent module. This observation is also evident from the data sheets.

C. "Smoke Test"

In this section, the "smoke tests" of the current and alternative Peltier elements are evaluated. With the currently used as well as with the alternative Peltier elements error messages occurred during the "smoke test". Firstly, the ambient temperature and secondly, the temperature inside the sample module are outside the specified range. Furthermore, the error message that the incubator temperature is exceeded is intentionally suppressed by respective parameter settings – otherwise the analyzer would abort the run to ensure the quality of the results.

<u>*Current Peltier elements*</u>

Figure 3 shows the "smoke test" of the current Peltier elements.

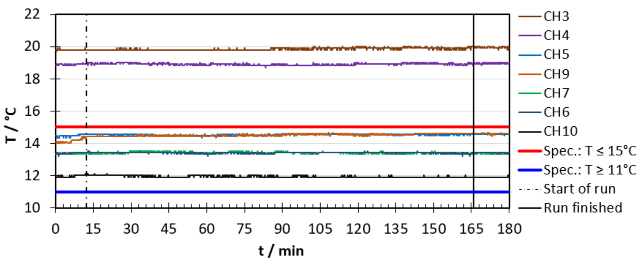

Figure 3: "Smoke test" of the currently used Peltier elements.

The origin corresponds to the starting time of the "smoke test", which initially begins with the priming process. After approx. $t = 12$ min, priming is completed, and the test run starts. Analogously to the "cold start test", the ancillaries do not reach the target temperature range. The moment when the "smoke test" is finished, the temperature in the rearmost ancillary was $T = 20.00$ °C and the temperature in the frontmost ancillary was $T = 19.00$°C. All measured integral temperatures were found to be within target range of $T = 13$ °C ± 2 °C. In addition, out of 288 jobs, 276 jobs were successfully processed. According to the specifications, only 240 jobs need to be completed successfully [6].

<u>*Alternative Peltier elements*</u>

A similar trend can be seen in the "smoke test" of the alternative Peltier elements (see Figure 4).

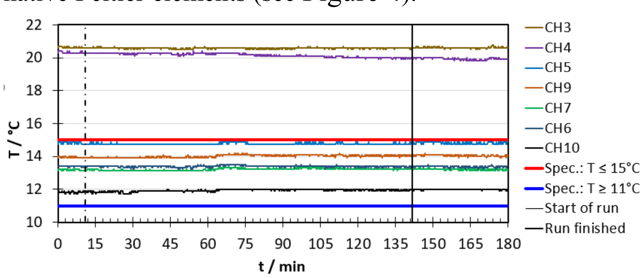

Figure 4: "Smoke test" of the alternative Peltier elements.

As anticipated, the temperatures in the ancillaries exceed the target temperature range. The moment when the "smoke test" is finished, the temperature in the rearmost ancillary was $T = 20.80$ °C and the temperature in the frontmost ancillary was $T = 20.00$ °C. The maximum temperature measured in CH5 sometimes peaks at $T_{max} = 15.15$ °C and the mean value is $\bar{x} = 14.88$ °C. All other measured integral temperatures were found to be within target range of $T = 13$ °C ± 2 °C (see Figure 4). Since the error message that the incubator temperature is exceeded has been suppressed, the temperature in the integrals of the reagent module is expected to remain in range under normal operating conditions. In addition, out of 288 jobs, 246 jobs were successfully processed [6].

III. Conclusion and Outlook

Compared to the currently used Peltier elements, the alternative Peltier elements require more time during the "cold start test" to reach the specified temperature range. On average, the specification using the alternative Peltier elements is met for two measurement positions whereas the specification using the currently used ones can be met for three measuring positions. Furthermore, the alternative Peltier elements require on average 6.8 % more power to achieve sufficient cooling of the reagent module. Hence, the power increase is 2.8 percentage points higher than the pre-estimated power increase of 4 % based on the technical specifications.

During the "smoke test", the error messages occurred that the temperature inside the sample module and the ambient temperature were exceeded. Nevertheless, the measured reagent temperatures are within range for all measuring positions, except for the ancillaries. Using the alternative Peltier elements, the mean temperature in CH5 is also within the specified range with $\bar{x} = 14.88$ °C. Furthermore, 30 fewer jobs are executed using the alternative Peltier elements which is not related to the cooling capacity of the Peltier elements or the climatic conditions. Anyway, the specification of 240 successfully executed jobs has been met in this respect.

Since the tests were conducted under extreme climatic conditions, which are rarely applicable in practice, and the specifications can still be met, the verification tests are accepted.

IV. Acknowledgment

First of all, I would like to express my special thanks to my supervisor Dirk Herrmann and the head of department Thomas Gratzl, as well as the company STRATEC SE, who made it possible for me to carry out this project. I would also like to express my special thanks to Prof. Dr. Volker Bucher for the supervision on the part of the Furtwangen University.

V. References

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