Development of a Passively Cooled Outdoor Telecom Power Enclosure

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Abstract

This paper documents the development of a passively cooled outdoor electronics enclosure consisting of six 1.2kW AC/DC rectifiers (7.2kW total output power). Commercially available fan cooled rectifiers were used as a starting point and modified to be passively cooled using heat pipes and naturally-cooled heat sinks without changing the layout of the original circuit board. Several designs were considered, tested and modified to develop a fully passive thermal solution. The prototype was tested at ambient air temperatures of 26°C, 36°C and 46°C and it delivered 98.8%, 85.7% and 80.7% of its nominal output power at each of these temperatures, respectively.

Keywords

electronics packaging, outside plant power enclosures, heat pipes, natural convection, passive cooling

1. Introduction

As the demand for global communication rises, the telecommunication infrastructure continues to expand and increase in capacity. Telecommunication companies are forced to continually upgrade their equipment, which typically results in higher input power demands. The expansion of coverage also requires the equipment to operate in new locations and frequently under new constraints, leading to new challenges for the design of cooling solutions. In remote areas these constraints are often due to harsh climate conditions, while in urban areas the level of acoustic noise can be a significant issue. Passive systems based on natural convection pose an attractive alternative to active systems based on forced convection. Since passive systems do not contain moving parts, such as fans or blowers, they are inherently noise-free. Moving parts are not only an acoustic problem, fan reliability is a significant concern that increases the operational costs of power supply equipment. By transitioning to passive systems it is also possible to increase the efficiency of electronic devices as the parasitic power required by the fans is eliminated. The main drawback of passive systems is that the heat sinks must be large due to the low convective heat transfer coefficient.

The work presented in this paper is a result of a collaboration between Alpha Technologies, a major power electronics manufacturer, located in Burnaby, British Columbia, Canada and the Laboratory for Alternative Energy Conversion at Simon Fraser University.

2. General Problem Overview

Outdoor enclosures, often called outside plant (OSP) power systems in the electronics community, are used for housing electronic equipment. Alpha's OSP's include a power supply, which, depending on the equipment input and the available power source, consists of AC/DC rectifiers, DC/DC converters, or, in special cases, DC/AC inverters. If necessary, batteries can be installed for backup power. To protect the equipment from water and dust the enclosures are fully sealed, which causes accumulation of heat. The sizes of telecom outdoor power enclosures typically range from small, with volume is as low as 30 dm^3), up to large, with volume of 850 dm^3. Output power levels range from hundreds of watts to approximately 30kW.

Various cooling strategies are used to keep the inside air temperature within allowed limits. The simplest strategy, which is currently limited to very low power outputs (650W [1]), relies solely on natural convection. In this case, heat from the electronic equipment is transferred to the walls by natural convection within the enclosure. At the exterior of the enclosure the heat is then rejected to the ambient, also by means of natural convection. Figure 1 a) shows an example of a naturally cooled outdoor enclosure. Larger enclosures with higher power ratings are equipped with fans and air-to-air heat exchanger (Figure 1b). One set of fans circulates the inner air through the hot side of the heat exchanger, while the second set of fans forces the ambient air through the cold side of the heat exchanger, without mixing the two air streams. In addition to this, smaller fans are typically embedded in the packaging of the electronic equipment for local heat removal. In case of large, high power enclosures, or when the installed equipment is especially sensitive to high temperatures, the air-to-air heat exchanger is replaced by an air conditioning unit as shown in Figure 1c).

3. Research objectives

The goal of this research, as defined in collaboration with the industrial partner, was to develop a proof-of-concept demonstration of a passively cooled outdoor telecommunication enclosure. The system was required to be built into an existing, commercially available, 56 cm x 56 cm x 25 cm enclosure, which is shown in the Figure 1a. Contrary to the standard internal layout, which includes space designated for customer equipment and batteries, the prototype was required to only contain six commercially available 48Vdc Cordex HP 1.2kW rectifiers (Figure 2). Each of these rectifiers has an internal cooling fan. The goal of this project was to passively cool the rectifiers so that these fans could be eliminated without modifying the layout of the circuit board. The overall rectifier efficiency is 94% [2] resulting in 72W heat dissipation (432W for the whole enclosure). As per the requirements of the industrial partner, the system was required to operate up to a maximum ambient air temperature of 46°C

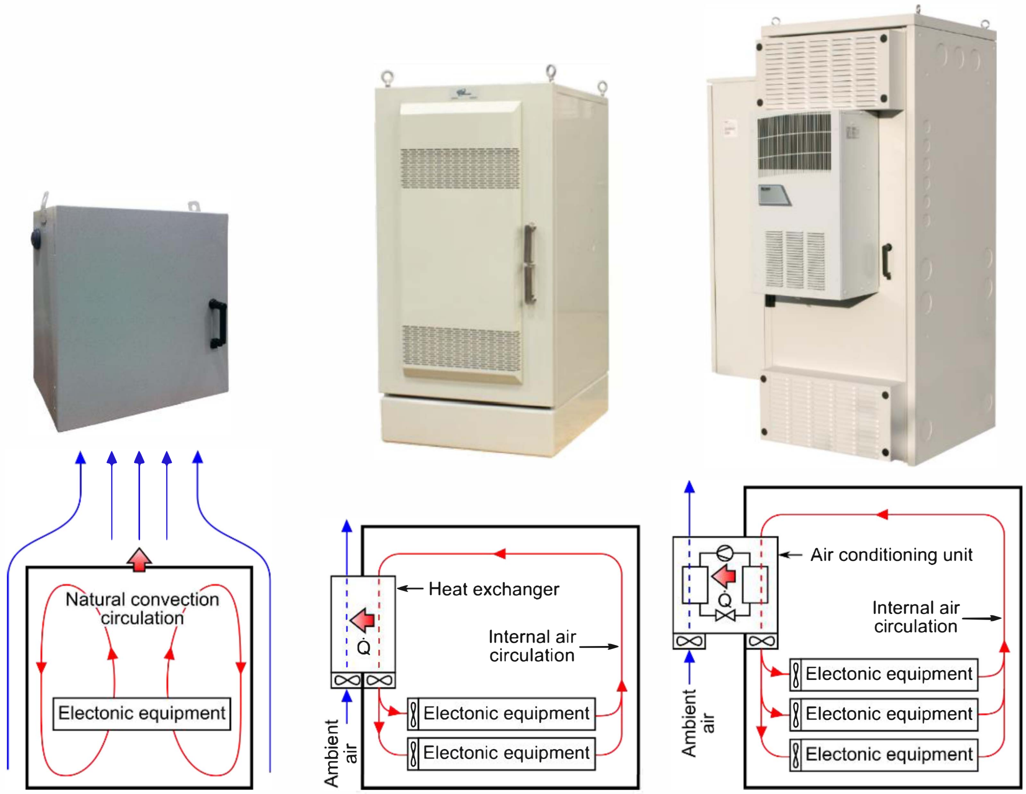

Figure 1: Schematic visualizations (bottom) and photographs (top) of outdoor enclosures cooled by a) natural convection, b) air-to-air heat exchanger, c) air conditioning unit.
Top photographs source: [1], [3], [4].

according to the Telcordia Technologies Generic Requirements [5].

4. Heat Pipes

Heat pipes (Figure 3) are a mature and inexpensive technology that provides a reliable method of heat transfer. They offer high cooling capacity, negligible temperature drop along the heat transfer path and, more importantly, are completely passive. Heat pipes are commonly used for CPU and GPU cooling. Their application in power electronics is, however, relatively new. Kobiashi et al. [6] attempted to improve the heat exchanger cooling strategy of the OSP similar to the one shown in Figure 1b using a heat pipe based heat sink. Hong et al. [7] developed a geothermally cooled outdoor cabinet that used aluminum-ammonia heat pipes to reject heat from the enclosure into adjacent ground. Biela and Kolar [8] used flat heat pipes for magnetic devices cooling.

Figure 2: Original packaging of the rectifier with and without the cover

Due to the applied nature of using heat pipes in electronics enclosures, the related research is mostly performed in corporate R&D projects whose results are not often published in scientific journals and made available to the broader engineering community. There are, however, two patents in the area: US 7,031,158 B2 (heat pipe cooled electronics enclosure) and US 8,284,004 B2 (heat pipe supplemented transformer cooling).

5. Prototype development

5.1. General concept

The critical heat-generating components were connected to naturally-cooled heat sinks with heat pipes, while the rest of the components dissipated heat to the air inside the enclosure. Ideally, the design change from forced-convection cooling to passive cooling would not affect the temperatures of all the components. While a severe increase in component temperature can cause an immediate failure, a moderate increase may only affect long term reliability. As this project required only a working, proof-of-concept prototype, the long term reliability was not considered.

An assessment of the original fan cooled rectifier identified the critical heat-generating components: the power switches (MOSFET), the diodes, and the main transformer. The cooling system design connected these components to the heat sink using heat pipes. The original forced convection heat sinks were replaced with one, large, anodized aluminum, vertical plate-fin natural-convection heat sink. The heat sink is 56cm high, 20cm wide and 6.6cm thick and consists of a 6 mm base plate with 23 fins at a 7 mm fin spacing. It was selected with consideration to the size of the enclosure rather than to the heat dissipation capacity. Each rectifier was connected to a separate heat sink, forming six modular sub-assemblies. The final

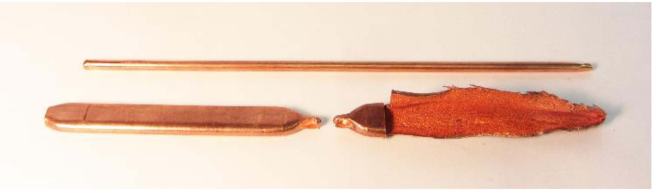

Figure 3: Circular heat pipe (top), flat heat pipe (bottom left) and cut flat heat pipe showing a sintered metal wick structure (bottom right)

prototype consisted of the six sub-assemblies mounted to a single enclosure.

5.2. Circular heat pipes

The first and second designs were based on circular heat pipes and are shown in Figure 4. Attaching circular heat pipes to the flat surfaces of the components and heat sink poses an additional thermal resistance due to the linear contact. In order to mitigate this problem, aluminum blocks with machined grooves were installed at the ends of the heat pipes. Testing of the first design resulted in a rectifier failure at loads higher than 65% at 46°C. Measurements revealed significant temperature drops between the aluminum blocks and the heat sink due to the large thermal contact resistance between the aluminum blocks and the heatsinks. The second design was meant to address this problem by machining grooves on the back side of the heat sink and attaching the heat pipes directly to the base of the heat sink. Even though a reduction in the temperature drop was observed, the test still resulted in a rectifier failure.

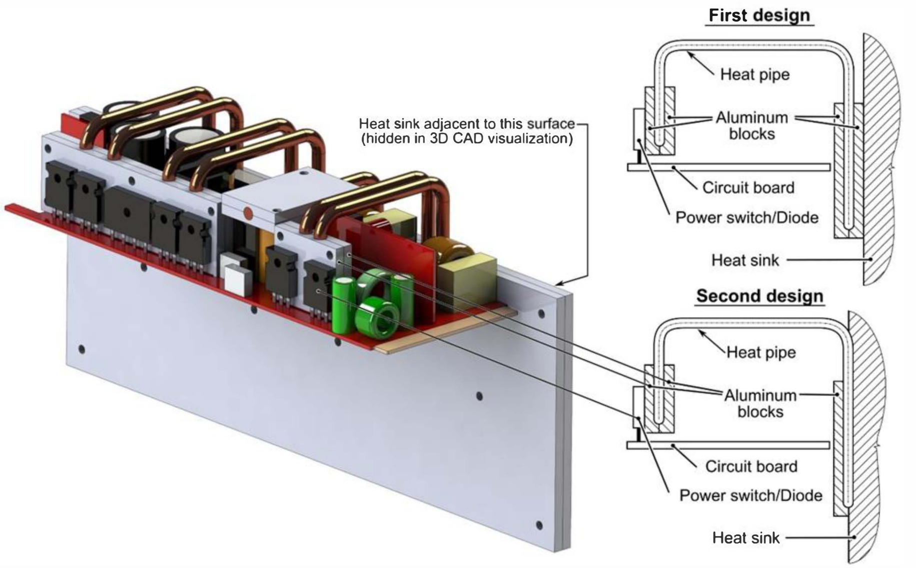

Figure 4: CAD visualization (left) and schematic section view (right) of the first and second design

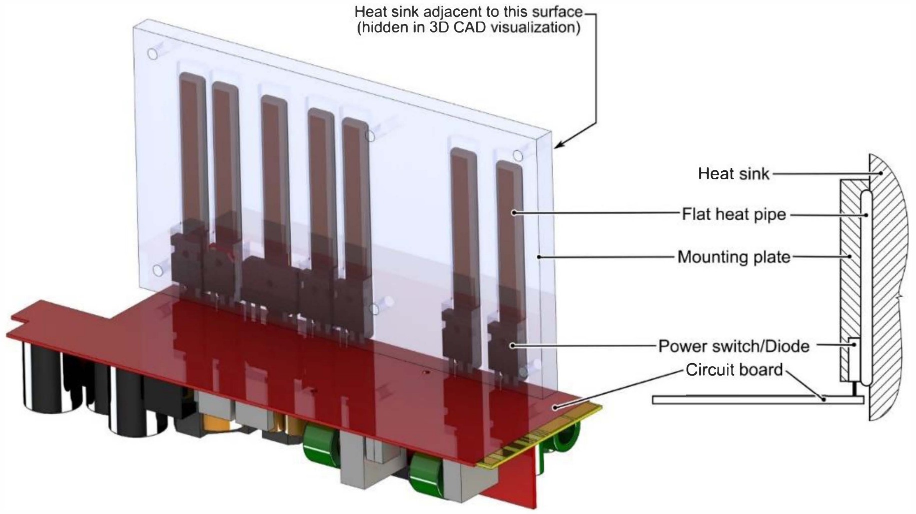

Figure 5: CAD visualization (left) and schematic section view (right) of the third design

5.3. Flat heat pipes

In the third design, flat heat pipes were used to circumvent the poor contact between circular heat pipes and flat surfaces and no aluminum blocks were needed. The orientation of the power switches and diodes was also reversed. This allowed the heat pipes to be attached directly to the components on one side, and the heat sink on the other side, as shown in Figure 5. It should be noted that the heat pipes attached to the power switches and diodes were used in an alternative fashion and served only as heat spreaders, analogous to vapor chambers. Two additional flat heat pipes were used to connect the core of the main transformer to the heat sink and a small heat sink was added to the top of the inductor.

Testing of the third design showed that the temperatures of all the monitored components were satisfactory. Despite this the rectifiers failed during tests at full load. Visible damage was repeatedly observed in the part of the circuit board that controls the opening and closing of the power switches. The switches were removed from the board and analyzed, and it was found that high current from the power circuit penetrated the control circuit and damaged the control components. A circuit analysis suggested that the reason for failure was overheating of the main transformer. This was confirmed by infrared thermal imaging, which revealed hot spots in the windings of the transformer and inductors (the magnetic components).

The aim of the fourth design was to reduce the temperature of the windings of the magnetic components. While it is straightforward to cool down the windings with a stream of air, the complex geometry made passive cooling very challenging. Due to the late stage of the project a simple solution was sought. Thus, circular heat pipes were attached to the windings by metallic cable ties and high-temperature plastic zip ties. Thermal compound OMEGA 201 was used to improve the thermal contact between the windings and the heat pipes. Additional semicircular grooves were machined on the back side of the heat sink and the heat pipes were bent to fit in these grooves. An aluminum plate was used to press the heat pipes to the heat sink. The number of flat heat pipes used to cool down the core of the main transformer was reduced from two to one. The fourth design is shown in Figure 6.

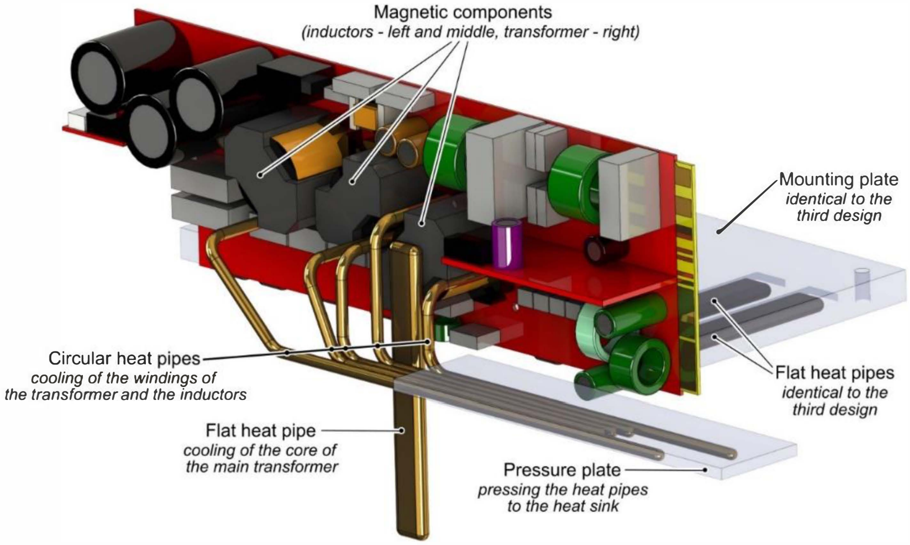

Figure 6: CAD visualization of the fourth design

5.4. Full prototype

The full prototype (Figure 7b) consisted of the enclosure with six sub-assemblies (Figure 7a). A set of three sub-assemblies was mounted on the rear wall of the enclosure while a single sub-assembly was mounted to the left, right and top walls. The following notation for the individual sub-assemblies is adopted: L – left, RL – rear left, RC – rear center, RR – rear right, R – right, T – top. The enclosure also contained a controller, which supervises communication and load sharing between the rectifiers, and wiring, which distributes the AC feed to all of the rectifiers and collects the DC output.

6. Passive enclosure testing and validation

Measurements were performed in a 4m x 4m x 4m environmental chamber at ambient temperatures of 26°C, 36°C and 46°C. Load banks with variable resistance were used to simulate real DC equipment. In the initial phase of the project, all the rectifiers were connected in parallel to a single load bank. The controller supervised load sharing based on information from temperature sensors on each of the rectifiers. Initial measurements showed that the top rectifier was operating at much higher temperatures due to stratification of the air in the enclosure. To ensure the top rectifier would not overheat, two separate load banks were used (Figure 8) so that the load imposed on the top rectifier could be controlled separately.

Figure 7: Sub-assembly consisting of a heat sink, heat pipes and rectifier (left); Full prototype (right)

The input AC voltage and current were measured by a NI 9225 module and a Fluke i200s clamp meter whose output was read using a NI 9205 module. DC voltage was monitored using a NI 9229 module. DC currents through the load banks were measured using shunts that were connected to a NI 9238 module. The web interface of the controller shows the live status of the individual rectifiers, namely the current values and any alarm messages. This status data was recorded at 10 second intervals using a computer script.

T-type thermocouples together with a NI 9213 module were used to measure temperatures. Component temperatures were monitored only on the top and rear-center rectifiers as those two were operating in the most adverse conditions. To capture the vertical temperature gradient of the stratified air inside the enclosure, three thermocouples were installed in the enclosure at distances of 9 cm, 22 cm and 38 cm from the bottom. One thermocouple was mounted on the side-most fin of each of the heat sinks. Ambient temperature was monitored by a thermocouple located approximately 30 cm behind the rear heat sinks. All of the measurement modules were housed in a NI cDAQ 9178 data acquisition system. The data was collected using a laptop and a custom-designed LabVIEW interface.

The quality of the design is defined by the maximum power that can be delivered at a given ambient temperature. This was tested by gradually increasing the load until the web interface of the controller reported an alarm or until the output DC voltage dropped below the nominal voltage of 48 V.

7. Results and discussion

The power measurement results are shown in Table 1. The system was not able to deliver the full nominal power at elevated temperatures and only 80.7% performance was achieved at 46°C. The power of the five side-mounted rectifiers dropped at higher temperatures, however, the power of the top rectifier remained constant. The data in Table 2 shows that the temperatures of the top rectifier were always higher than the

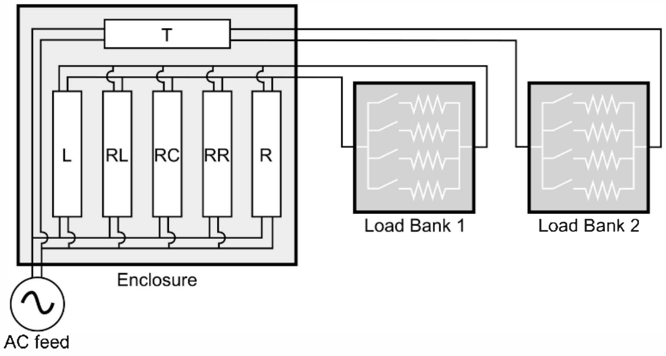

Figure 8: Scheme of electrical connection during the final test

Ambient Temperature [°C]	Total power [kW]	% of Maximum Nominal Power (7.2kW)	Individual rectifier power [kW]					
			L	RL	RC	RR	R	T
26	7.11	98.8	1.21	1.17	1.18	1.20	1.19	1.16
36	6.17	85.7	1.02	1.01	1.00	0.99	1.00	1.16
46	5.81	80.7	0.86	0.87	0.91	0.94	1.07	1.16

Table 1: Results of output power measurement

temperatures of the rear-center rectifier. This is in contrast to the results of the power measurements, as rectifiers operating at higher temperatures would be expected to deliver lower power. The performance of the system appears to be limited by the communication circuitry rather than by thermal runaway of the power components. This conclusion can be supported by the following two arguments. When single sub-assemblies were tested separately at elevated temperatures there was no power drop. Further, for the rear-center rectifier, the temperatures of the magnetic components, which were identified as performance bottlenecks (see section 5.c), are highest at the lowest ambient temperature. Thus, it is clear that during the final tests the performance was not limited by the temperatures of the magnetic components.

One possible explanation for the unexpected behavior was a controller overheating. To test this hypothesis, the controller was placed outside of the enclosure, but no change in system behavior was observed. Due to time constraints, no further troubleshooting was done. Nevertheless, it is reasonable to assume that by solving the communication issue, or by using a separate load bank and controller for each of the rectifiers, it would be possible to achieve the full nominal performance even at elevated temperatures.

8. Conclusion

A prototype passively cooled outdoor enclosure with six 1.2kW rectifiers was built. It was not able to deliver the full nominal power at elevated ambient temperatures. Power outputs of 85.7% and 80.7% of the nominal power were achieved at 36°C and 46°C ambient temperatures, respectively. The output power appeared to be limited by malfunctioning communication circuitry. It was shown that a fan cooled design can be converted into natural convection design without changing the layout of the circuit board and that a 56 cm x 56 cm x 25 cm enclosure containing six 1.2 kW rectifiers (7.2 kW) can be passively cooled.

Acknowledgments

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Ambient Temperature	Inner Air Temperature			Heat Sink Temperature						Rear Center (RC) Rectifier						Top (T) Rectifier					
	Height = 9 cm	Height = 22 cm	Height = 38 cm	Left (L)	Rear Left (RL)	Rear Center (RC)	Rear Right (RR)	Right (R)	Top (T)	Main Transformer Core	Main Transformer Winding	Inductor 1 Core	Inductor 1 Winding	Inductor 2 Core	Inductor 2 Winding	Main Transformer Core	Main Transformer Winding	Inductor 1 Core	Inductor 1 Winding	Power Switch 1	Power Switch 2
■26	58	68	72	52	56	54	57	48	60	93	111	123	115	91	98	116	113	131	130	88	83
■36	60	67	74	56	60	58	60	53	65	87	99	111	103	85	91	120	115	133	132	93	89
■46	67	74	81	63	68	67	69	62	74	93	104	112	106	91	96	131	125	142	139	102	98

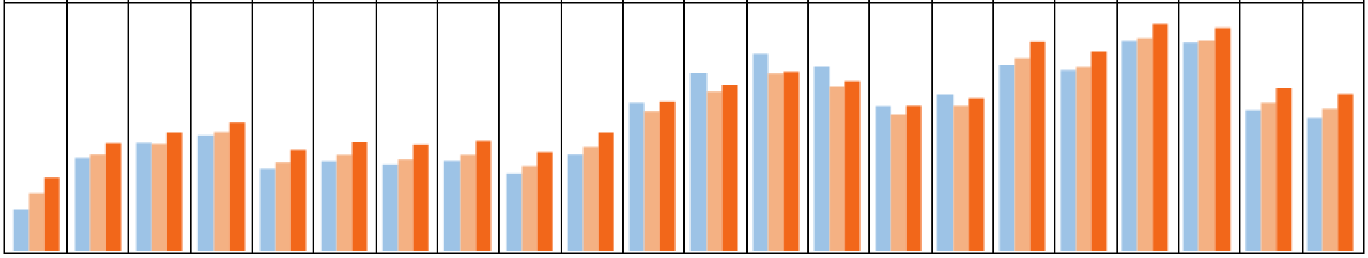

Table 2: Results of the steady state temperature measurement [°C]. Visualization of the measurements at individual ambient temperatures is provided at the bottom using a bar plot: blue bar - 26°C, orange bar - 36°C, red bar - 46°C

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