Experimental investigation on the long-term operational behaviour of two-phase closed thermosyphon bundles for passive heat transfer from spent fuel pools under normal, abnormal, and accident conditions

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ABSTRACT

Two-phase closed thermosiphons (TPCT) are passive heat transfer devices that can ensure the safe operation of nuclear facilities in the event of a power failure or other malfunction. In the present investigations at the ATHOS (Atmospheric Thermosiphon cOoling System) test facility of the IKE (Institute of Nuclear Technology and Energy Systems, University of Stuttgart), the long-term operation of TPCTs under different heat transfer rates, temperatures and cooling airflow conditions was investigated. The investigations show that a reliable long-term operation is possible. Maximum heat transfer rates of up to 900 W per TPCT were achieved.

INTRODUCTION

Since the reactor accident at the Fukushima Daiichi nuclear power plant in Japan, the research focus in the field of heat management has shifted towards passive heat removal systems. In laboratory tests passively operating systems, such as TPCT, showed that the the decay heat in spent fuel pools can be removed with TPCT in principle. TCPTs are wickless, gravity-driven heat pipes whose operating principle is based on the evaporation and condensation of a working fluid in a sealed pipe. Thus, the heat transfer cycle takes place within the sealed pipe, which distinguishes this operating principle from classic cooling cycles. A detailed description of the operating principle can be found in works by Faghri [1], Reay and Kew [2] or Groll and Rösler [3].Despite of the simple thermodynamic principle of TPCTs the exact thermodynamic processes within a TPCT are not fully understood, even after many years of research in this field [3]. The behaviour of TPCTs strongly changes with the selected diameter, length and working fluid, therefore, suitable similarity equations must always be developed to reliably describe the heat transfer of the TPCTs. Especially in the context of the approval for nuclear facilities, an exact understanding of the TPCT behaviour under different operating conditions is necessary. Initial research efforts were made by Graß et al. [4] [5] [6]. In corresponding laboratory tests it could be proved that a single TPCT could dissipate up to 2 kW of heat at 60° C heat source temperature. Initial tests with ATHOS showed that at a spent fuel pool temperature of 60° C about 3.2 kW heat can be dissipated by a 3x3 TPCT tube bundle.

In the context of this study, the work of Graß et al. [5] is to be extended. In the ATHOS test facility which is equipped with a water tank as a heat source and a chimney with controllable cooling airflow as a heat sink, an extended test matrix for long-term observation of TPCT bundles is to be carried out. The setup provides realistic boundary conditions of the application planned later in a spent fuel pool of a nuclear facility.

EXPERIMENTAL SETUP AND PROCEDURE

The ATHOS test facility is located at the IKE of the University of Stuttgart. It is an experimental setup installed that has two 3 m³ water tanks as a heat source. The water in the tanks is heated with screw-in heaters mounted in the lower tank area. The screw-in heaters are mounted in two horizontal rows of 5 each and have a maximum heating power of 10 kW. Two different TPCT bundles are installed in these water tanks with a base area of 1 m². These are a straight 3x3 tube bundle and a double bent 2x2 tube bundle, the exact geometry can be seen in Figure 1. The pipes, made of 1.4301 stainless steel, with an internal diameter of 32 mm and a thickness of 1.5 mm, are immersed 1.5 m into the water tanks. The TPCTs are filled with distilled and degassed water as working fluid. A filling ratio of 70 % is selected, which corresponds to a quantity of 890 g and a filling height of about 1 m in the tube. Through an opening in the outer shell, the pipe bundles are led into a 7.5 m high chimney in which the cooling airflow can be controlled via 6 fans. Approximately 5 m of the pipe is in the chimney. This length corresponds to the condensation zone, whereby the airflow of the chimney starts after 1 m.

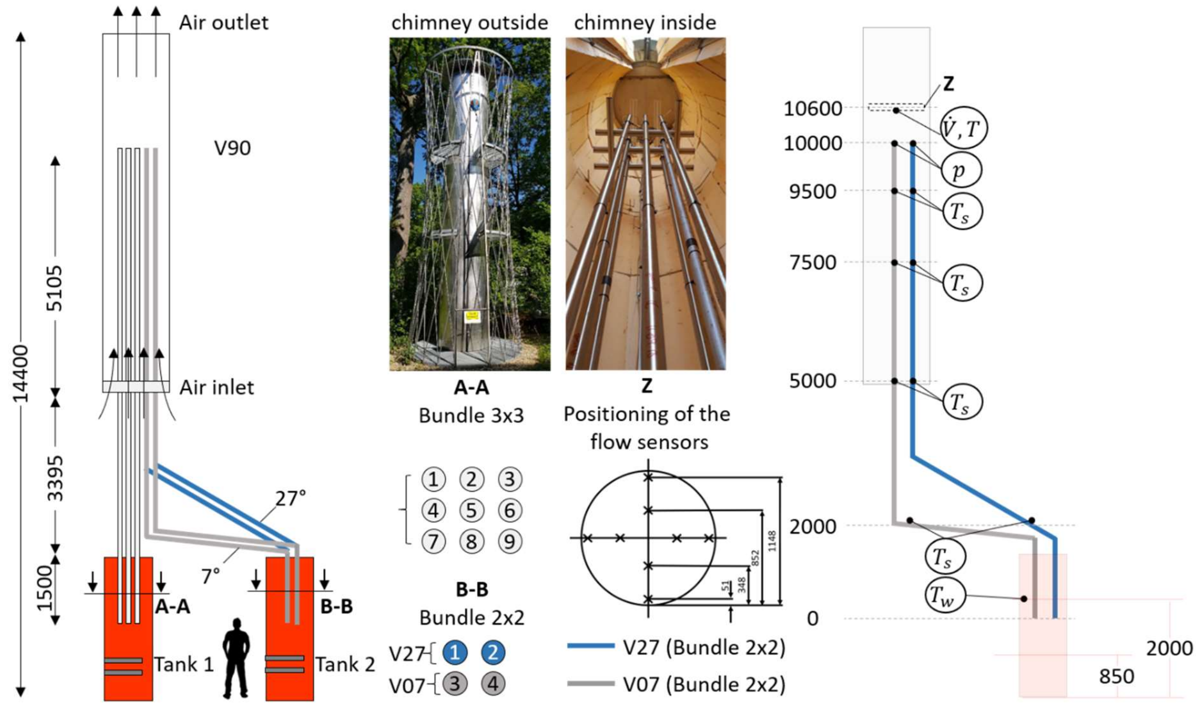

Figure 1 Schematic of the ATHOS test facility and instrumentation scheme of the temperature sensors on the 2x2 TPCT bundle

The measurement technology of the test facility is designed to create a broad data basis in order to enable not only the optimisation of the heat transfer rates and bundle effects of TPCT but also a data basis for validiation of numerical simulations. The TPCTs are equipped over their entire lengths with Pt100 thermometers (measuring range -40° C to 200° C, accuracy ±0.35° K). The pressure measurement in the TPCT is carried out with absolute pressure transmitters (Keller PAA-33X, pressure range 0 to 3 bar, error of ±0.15 % on the final value). In the 2x2 pipe bundle, all TPCTs are equipped with a absolute pressure transmitter. The flow measurement in the chimney is carried out by 8 thermal anemometers which are installed according to the DIN EN 16211 [7] standard (see Figure 1). These sensors have an accuracy of ±5 % of the measured value plus 0.4 % of the final value with a measuring range of 0-10 m/s, and the integrated temperature sensors have an accuracy of ±1°K for a measuring range of -20° to 70° C.

RESULTS

The results of the 2x2 TPCT bundle configuration are presented as follows. The influence of different cooling airflow velocity impost in different operating conditions of the water tank on the heat transfer rates of TPCT was investigated. The operating conditions are derived from the standard of the Nuclear Safety Standards Commission KTA 3303 [8] with 45°, 60° and 80°C water tank temperature corresponding to normal, abnormal and accidental thermal operating conditions of spent fuel pools in nuclear power plants. These three thermal operating conditions are compared for three defined cooling airflow velocities As the measurements were carried out under varying weather conditions, e. g. changing wind conditions, the cooling airflow velocity in the chimney was not constant with a constant fan setting. Therefore, the division into 0.5 m/s intervals was carried out for the flow range 0 - 2.5 m/s. The measurements were carried out in a long-term interval of 3 days. All measurements were repeated to prove stable long-term operation and to expand the data basis through changing weather conditions.

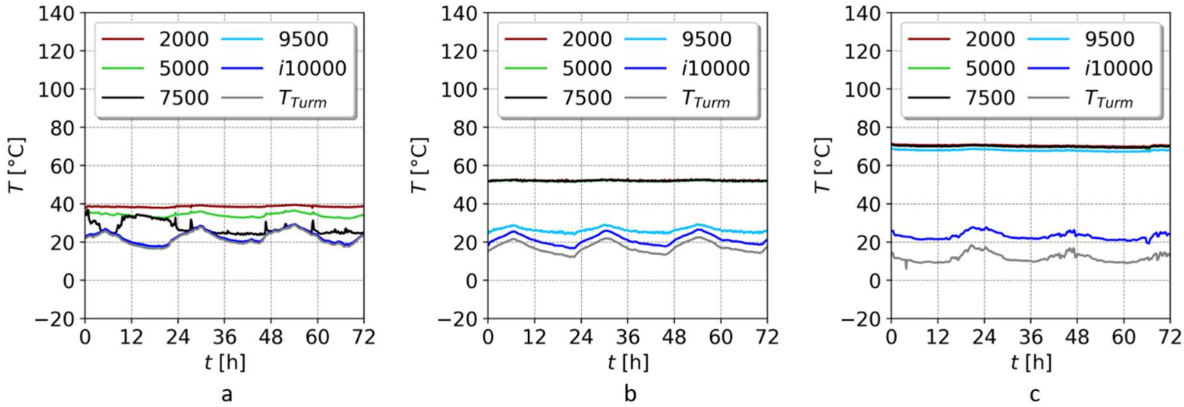

Figure 2 Temperature curves of TPCT V27-1 at 45 °C (a), 60 °C(b) and 80 °C (c) water tank temperature and airflow velocities of 1 - 1.5 m/s

Figure 2 shows an example of the temperature curves at different heights along the thermosiphon V27-1 (see Figure 1) during continuous operation over 3 days at low airflow velocity between 1 and 1.5 m/s. The numbers given in the legend correspond to the temperature measurement position along the TPCT height. The sensor at the height of 10,000 mm is located inside the TPCT while the other sensors are contact sensors at the outer TPCT surface. T_{Turm} shows the cooling air temperature entering the chimney. Several conclusions can be drawn from Figure 2. For a water tank temperature of 45° C (a), the TPCT does not operate in a stable state. This can be seen from the strong fluctuation of the sensor at 7,500 mm. For a tank temperature of 60° C (b), a stable operating state is obtained. However, in the upper area of the condenser at 9,500 mm the temperature still approaches the outside ambient temperature. This suggests that the supplied heat is dissipated quickly, and therefore the entire length of the condensation zone of the TPCT is not required. For a water tank temperature of 80° C (c), it can be seen that the temperature is nearly uniform over the entire length of the TPCT condensation zone. The temperature of the condensation side is not affected by the day/night variation of the ambient heat sink. The only temperature that fluctuates with the outside ambient temperature is the internal temperature sensor at a height of 10,000 mm. Here it is reasonable to assume that a small layer of non-condensable gas has formed due to outgassing processes of the working fluid since the first filling of the TPCT 3 years ago. The work of Caceres et al confirms this assumption [9].

However, the temperature courses indicate that a long-term operation is possible even after several years. The TPCTs were able to reach an average heat transfer performance of about 115 W, 325 W and 650 W per TPCT at 45° C, 60° C and 80° C water tank temperature. The highest heat transfer performance of a TPCT within the entire measurement campaign was about 900 W at a water tank temperature of 80° C and a cooling airflow velocity between 2.0 and 2.5 m/s.

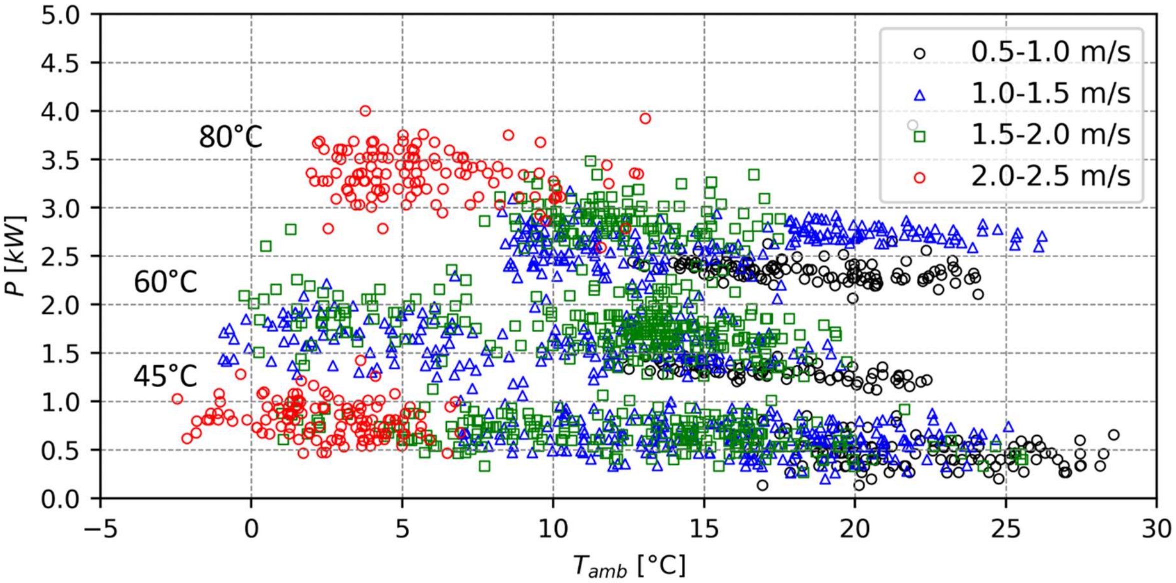

Figure 3 Hourly mean of heat transfer performance of all measurements versus ambient temperaturefor different airflow velocity in the chimney

Figure 3 shows the overall view of the measurements plotted against the ambient temperature and the heating power applied to the water tank. Hourly averages for the ambient temperature, the airflow velocity and the transferred heating power were determined from all the measurements carried out. Three heating power clusters emerge, which result from the selected water tank temperature (45/60/80 °C). Within the clusters, the different airflow velocities are indicated. For the cohort with 45° C water tank temperature, no clear influence of the airflow velocity can be determined. Results from previous measurements from Graß et al. [5] as well as own measurement data allow the conclusion that the TPCTs are not in a stable operating point at a water tank temperature of 45° C, and thus most of the heat is dissipated due to heat conduction within the thermosiphon. For the cluster with 60° C water tank temperature, a first “layering effect” occurs due to the airflow velocity i. e. there is a tendency for a higher heat output to be transferred at a higher airflow velocity. This becomes even more visible in the third cohort at a water tank temperature of 80 °C. Another finding is that a larger temperature difference between the heat source and the heat sink results in a higher total heat transfer which is more or less valid for all measurements. This is based on the relationship that the heat transfer is the ratio of the heat source/heat sink temperature difference and the thermal resistances along the TPCT [3, 10]. Since these thermal resistances do not change as much as the driving temperature differences for selected boundary conditions, the thermal resistance of TPCT is the parameter with the major impact.

CONCLUSION

The behavior of TCPT in continuous operation under variation of boundary conditions, temperature of the heat source and speed of the cooling air flow was investigated. For this purpose, long-term tests were carried out at the ATHOS test rig under realistic boundary conditions.

1. The operational capability of TPCT over a long period of time could be demonstrated.
2. The effect of higher air-cooling flow velocitiys on the heat transfer of TCPT was demonstrated when the driving temperature difference was sufficiently large.
3. It has been demonstrated that as the driving temperature difference increases, the heat transfer efficiency increases.
4. At the peak, an average power of up to 900 W per TCPT of a 2x2 bundle was dissipated.

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REFERENCES

[1] A. Faghri, Heat Pipe Science and Technology, Global Digital Press, 2016.
[2] D.A. Reay, Heat pipes: Theory, design and applications, Sixth edition (Online-Ausg.), Elsevier, Amsterdam, 2014.
[3] M. Groll, S. Rösler: Operation Principles and Performance of Heat Pipes and Closed Two-PhaseThermosyphons. Journal of Non-Equilibrium Thermodynamics 17 (1992) 2
[4] C. Graß, R. Kulenovic, J. Starflinger: Experimental Investigation on Passive Heat Transfer by Long Closed Two-Phase Thermosiphons. International Journal for Nuclear Power (2017), S. 481–485
[5] C. Graß, R. Kulenovic, J. Starflinger, Atmospheric spent fuel pool cooling by passive two-phase closed thermosyphons, Atw Internationale Zeitschrift fuer Kernenergie 50 (2019) 427–431.
[6] C. Graß, R. Kulenovic, J. Starflinger, Experimental Investigation on Atmospheric, Passive Spent Fuel Pool Cooling by Two-Phase Closed Thermosyphons, Proceedings of 18th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, NURETH-18 (18-23 August, 2019).
[7] DIN EN 16211 Lüftung von Gebäuden – Luftvolumenstrommessung in Lüftungssystemen – Verfahren; Deutsche Fassung EN 16211:2015
[8] KTA 3303:2015-11. Wärmeabfuhrsysteme für Brennelementlagerbecken von Kernkraftwerken mit Leichtwasserreaktoren
[9] S. I. Cáceres Castro, M. Kirsch, R. Kulenovic, J. Starflinger, Experimental investigation on the startup behavior of a straight two-phase closed thermosyphon bundle for passive heat transfer from spent fuel pools, KERNTECHNIK 2022 Young Scientists Workshop, Leipzig, (21-22 Juni, 2022)
[10] Verein Deutscher Ingenieure, VDI-Wärmeatlas. 11 Auflage, Berlin, Springer Vieweg, 2013