Experimental investigation on the startup behavior of a straight two-phase closed thermosyphon bundle for passive heat transfer from spent fuel pools

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ABSTRACT

Two-phase closed thermosiphons (TPCT) are heat transfer devices, which could be used to improve nuclear power station safety by passively cooling the spent fuel pool in case of accidental conditions or station blackouts. The present experimental investigation is performed in the test facility ATHOS (Atmospheric THermosyphon cOoling System) at IKE (Institute of Nuclear Technology and Energy Systems, University of Stuttgart) in which the heat transfer performance of a long straight TPCT bundle can be investigated. The experiments deal with the startup behavior of a straight TPCT bundle for the case of an accidental scenario at a low and high air-cooling velocity of 0.7 m/s and 1.6 m/s. The results indicate a reliable startup of the TPCT bundle.

INTRODUCTION

Passive safety systems could play an important role of a nuclear plant safety concept, especially during accident conditions or in case of a station blackout. Currently, the decay heat from spent fuel pools (SFP) under normal operation is removed by an electrical cooling system. TPCTs are highly efficient passive heat transfer devices that could continuously remove the released decay heat without electrical components under normal, abnormal, or even accidental conditions. A TPCT is a wickless heat pipe that consists of three segments: evaporator, adiabatic and condenser section. Its operation principle is based on the continuous evaporation and condensation of a working fluid in a sealed closed pipe. A detailed overview of the operational principles, heat transfer limitations and performance characteristics are described by Faghri [1], Groll and Rösler [2] or Reay et al. [3].

Numerous designs and concepts for passive cooling of SFP have been proposed and introduced in the last decades. For example, Sutharshan et al. [4] introduced a safety system to remove decay heat from the reactor core. Xiong et al. [5,6] designed a novel loop heat pipe cooling system for passively removing the residual heat released in the SFP under accidental conditions. Graß et al. [7] built the facility ATHOS to study the applicability of 10 m long TPCTs for atmospheric passive SFP cooling. Kirsch et al. [8] carried out further investigations in ATHOS on the thermal behavior of a long bent TPCT bundle. However, these investigations focused on the long-term operation behavior under steady state conditions, where heat is removed and added at the same rate and TPCT temperature is constant.

Before a steady-state operation, the TPCT must be started from the ambient temperature. In transient state operation, the TPCT temperature varies with time due to the imbalance of the heat added and removed. Figure 1 shows three common temperature profiles along the TPCT during startup [1]. For example, the startup of Figure 1 (a) is achieved when the heat pipe is heated slowly so that the temperature along the heat pipe is closely uniform during the startup. The startup of a heat pipe with initially frozen working fluid is shown in Figure 1 (b). Gas-loaded startup (Figure 1 (c)) occurs when a non-condensable gas is present in the heat pipe.

In case of an accidental scenario, the heat input to the TPCT from the SFP will suddenly increase avoiding a slow and uniform increment of the temperature throughout the TPCT. This might represent damage in the TPCT due to overheating in the evaporator section. The investigation on the startup behavior of a straight TPCT bundle in this paper is proceeded by heating the TPCTs under accidental scenario conditions of the SFP. For comparison, tests are carried out at two different air-cooling velocities at similar ambient temperatures.

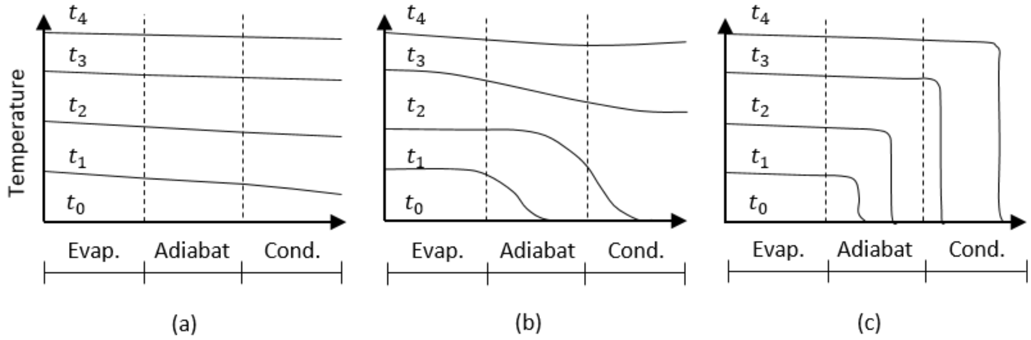

Figure 1: Transient axial temperature profiles during heat pipe startup: uniform startup (a), frozen startup (b) and gas-loaded startup (c) [1]

EXPERIMENTAL SETUP AND PROCEDURE

Figure 2 shows the ATHOS facility, built by Graß et al. [7], in which all experiments are carried out. The test facility consists of two TPCT bundles, a straight bundle of 9 TPCTs and a bent bundle of 4 TPCTs in a 3x3 and 2x2 aligned configuration. In this work, the focus is on the 3x3 straight bundle (see detail A-A in Figure 2). The smooth pipes are made of 1.4301 stainless steel and have 32 mm and 35 mm inner and outer pipe diameters. The bundles' evaporator sections are heated up by 3 m^3 water tanks, representing a model of a spent-fuel pool cooling on a smaller scale. The water in the tanks is heated with screw-in electrical heaters, each of them with a maximum output of 10 kW, mounted in two horizontal rows in the lower tank area. The adiabatic sections are thermally insulated. The upper part of the bundles, the condenser sections, are located inside a chimney. The cooling air enters the chimney at the bottom and exits at the top. Eight fans were additionally installed in the air inlet at the bottom of the chimney to impose a forced convective ambient airflow on the TPCT bundles. Every TPCT is filled with 890 g distilled degassed water, corresponding to a filling ratio of approximately 70 %. The heated and air-cooled lengths of the vertical TPCTs are 1500 mm and 5105 mm.

The outer surface temperature T_s of the straight TPCTs is measured with PT100 sensors at the heights 2000 mm, 5000 mm, 7500 mm, 9500 mm and 10000 mm. The inner temperature T_i is measured in TPCT 1, 5 and 6 at the height of 30 mm. The water temperature T_T in Tank 1 is measured at heights 0, 250 mm, 800 mm and 2000 mm. The absolute pressure in the condenser section of the bundle 3x3 is measured with absolute pressure transmitters (PAA-33X) in the TPCT 1, 5 and 6. The flow in the chimney is measured with 8 thermal anemometers (Schmidt SS 20.250). Detail B-B in Figure 2 shows the position of the anemometers according to the DIN EN 16211 standard. The Keysight data logger 34980 A and the computer software Agilent VEE are used for the measurement data acquisition.

For the design of fuel pool heat removal systems, the following limiting pool water temperatures are taken as a basis: 45 °C (normal operation), 60 °C (abnormal or malfunctioning storage tank cooling operation) and 80 °C (accidental operation) [9]. The experimental investigations in this paper are carried out considering the accidental operation temperature. For the experiments, the water in Tank 1 is heated with 40 kW from approximately 25 °C to 80 °C. The startup behavior of the straight TPCT bundle is investigated under two cooling boundary conditions, a low air-cooling velocity of 0.7 m/s, which is the natural convection flow inside the chimney, and a high velocity of 1.6 m/s (forced convection flow).

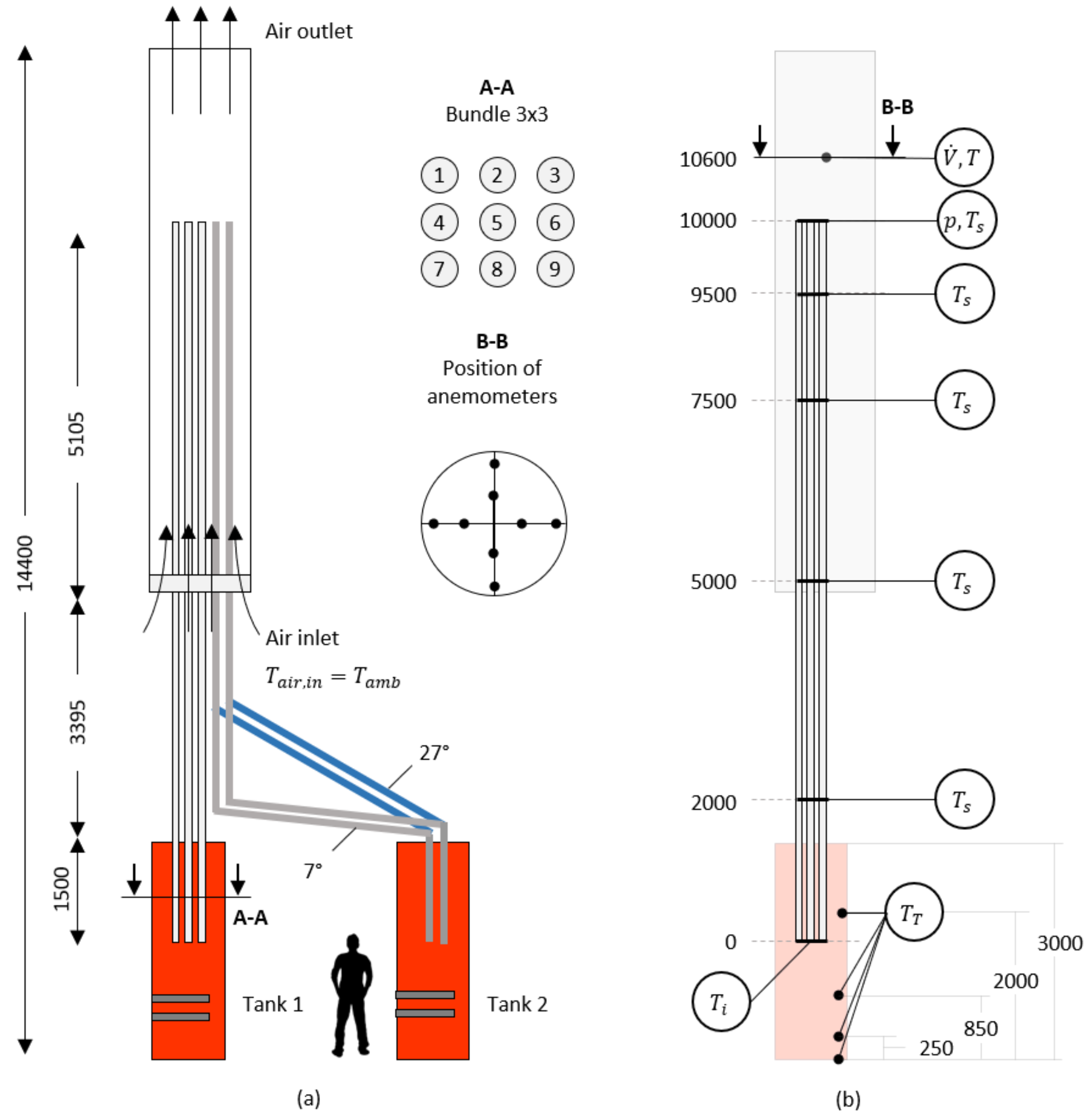

Figure 2: Schematic of ATHOS facility (a) and measurement positions in the straight TPCT bundle (b)

EXPERIMENTAL RESULTS

Prior investigations on this long straight TPCT bundle showed that potential bundle effects are negligible [10]. Therefore, the analysis of the conducted experiments in this work is focused on the TPCT6 at one side of the bundle. In Figure 3 and 4, the thermal startup operation at two different air-cooling velocities of the side-positioned TPCT6 is compared. The measurement frequency of data recording is 0.1 Hz.

Figure 3 (a) shows the temperatures at different heights of the TPCT versus the startup duration at a low air-cooling velocity of 0.7 m/s. The transient axial temperature profiles during the TPCT startup at this velocity are shown in Figure 3 (b). The red dashed lines indicate the separation of the evaporation, adiabatic and condenser section of the TPCT. The startup proceeds as follows: heat is conducted through the evaporator wall at constant heat rate, increasing only the working fluid temperature in the evaporator section. At approximately 0.6 h, evaporation begins to fill the vapor space until a height of

7500 mm with vapor. At this point, the vapor is slowly increasing the adiabatic and condenser section temperature by releasing its latent heat. At 1 h, this process reaches the height of 9500 mm and only after 1.5 h the temperature throughout most of the TPCT starts to become uniform. During the startup, it is noticeable that the temperature at the height of 10000 mm does not reach the operating temperature. The presence of the large axial temperature gradient of the height 9500 mm with lower positions, and the clear formed fronts during the startup indicates that a considerable amount of non-condensable gas, air, is present in the TPCT. In Figure 3 (b) the presence of the air can be recognized by the strong decrease of the temperature at the height of 7500 mm after 1 h. The move of the vapor-gas front into the top of the condenser section can be seen from 1 h to 1.5 h.

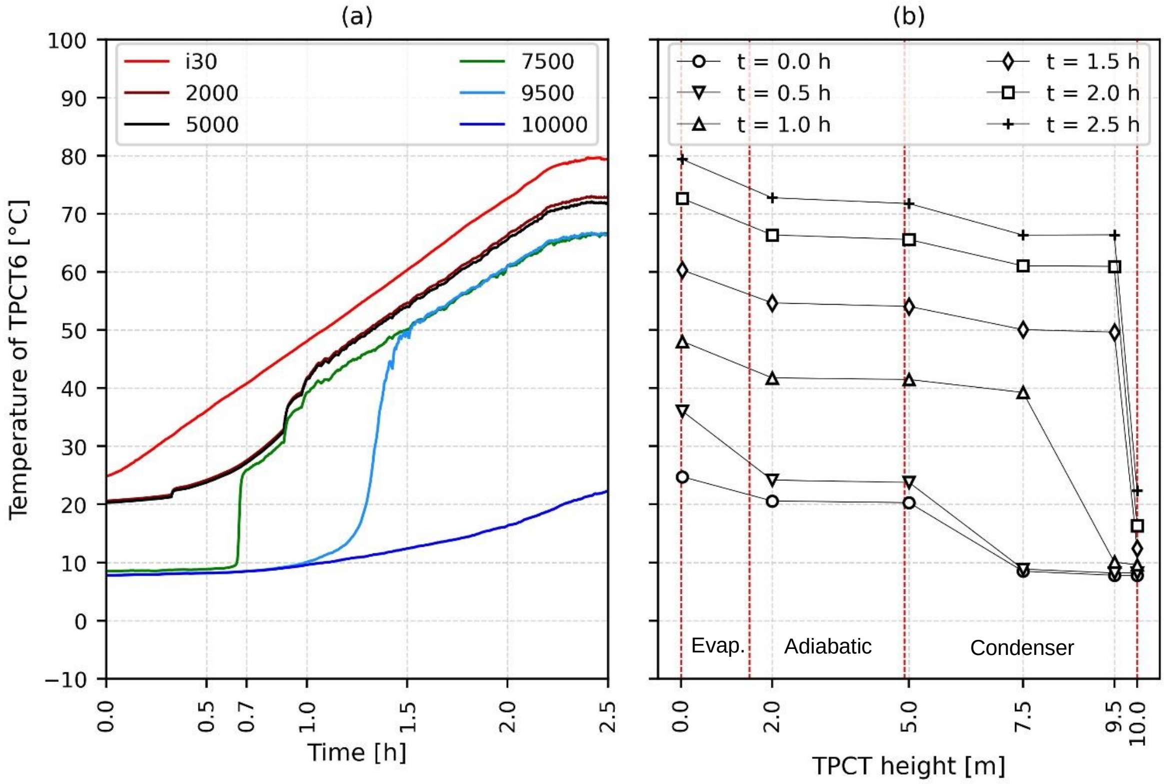

Figure 3: Temperatures at different heights of TPCT6 versus startup duration (a) and transient axial temperature profiles during TPCT6 startup at low air-cooling velocity of 0.7 m/s (b)

Figure 4 (a) shows the temperatures at different heights of the TPCT versus the startup duration at a high air-cooling velocity of 1.6 m/s. The transient axial temperature profiles during the TPCT startup at this velocity are shown in Figure 4 (b). Considering the transient axial temperature profiles of the TPCT, the startup behavior of the TPCT at an air-cooling velocity of 1.6 m/s is nearly identical to the one at 0.7 m/s. Similar to the previous experiment, an abrupt drop of the temperature at the height of 7500 mm after 1 h and a move of the vapor-gas front into the top of the condenser section from 1 h to 1.5 h can be seen.

One noticeable difference between both startups is the stratification of the temperatures throughout the TPCT after 1.5 h. This can be recognized in the inclination of the axial temperature profiles after 1.5 h, in Figure 3 (b) and Figure 4 (b), showing flatter profiles for the startup at 0.7 m/s and steeper profiles for the startup at 1.6 m/s. This rise in the temperature stratification is due to the increased air velocity which enhances the heat transfer coefficient in the condenser section, and thus the convective heat removal leading to lower wall temperatures.

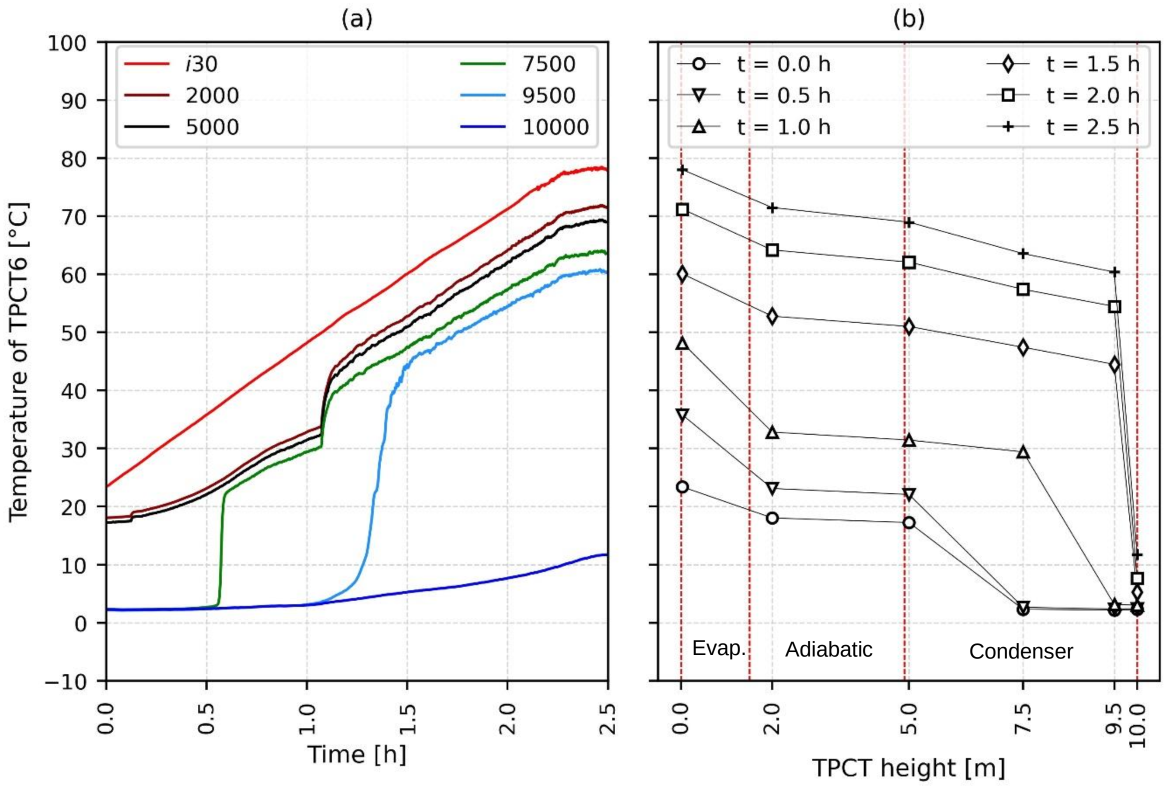

Figure 4: Temperatures at different heights of TPCT6 versus startup duration (a) and transient axial temperature profiles during TPCT6 startup at high air-cooling velocity of 1.6 m/s (b)

In addition, despite the presence of the non-condensable gas inside the TPCTs, can be concluded that the TPCTs show a reliable startup after a rise from 25 °C to 80 °C of the tank water temperature at both air-cooling velocities.

CONCLUSION

The startup behavior of a straight TPCT bundle in case of an accidental scenario (SFP temperature of 80 °C) was investigated. The experiments covered two cooling boundary conditions, a low air-cooling velocity of 0.7 m/s and a high velocity of 1.6 m/s. Following conclusions can be made:

1. The axial temperature profiles of the TPCT formed during its startup are attributed to the presence of a considerable amount of non-condensable gas (air) inside the TPCT.
2. The influence of the air-cooling velocity on the transient axial temperature profile during the TPCT startup is negligible.
3. The increased temperature stratification throughout the TPCT at a higher air-cooling velocity indicate an enhancement of heat removal and thus a reduction of the wall temperature along the TPCT.
4. The TPCT bundle exhibits a realiable startup after a rise from 25 °C to 80 °C of the tank water temperature around the evaporator section.

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