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# Heat transfer enhancement of micro oscillating heat pipes with self-rewetting fluid

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ABSTRACT

This paper discusses the heat transfer enhancement of micro oscillating heat pipes (MOHPs) using self-rewetting fluid (SRWF). To clarify the heat transfer enhancement mechanism, the thermo-physical properties (including surface tensions, contact angles and thermal conductivities) of SRWFs and deionized water have been comparatively analyzed. Furthermore, to find out the strengthening effect, experimental studies were performed on MOHPs. During the experiments, MOHPs with heat transfer length ($L$) of 100, 150 and 200 mm, consisting of 4 meandering turns and inner diameter ($D_i$) of 0.4, 0.8, 1.3 mm were adopted. SRWF and deionized water were employed as the working fluids. The results showed that, due to the unique property that the surface tension increases with increasing temperature, the SRWF can spontaneously wet the hotter region. The capillary resistance of the SRWF was much smaller than that of the deionized water, which is conductive to improving the circulation efficiency of the working fluid. Compared with the water, as the working fluid of the MOHPs, the SRWF exhibited much better thermal performance, which can decrease the thermal resistance and extend the effective operation range of MOHPs.



## 1. Introduction

The development trend of electronic devices, such as LED chips and CPU chips, gradually become miniaturized and integrated, which account for the over concentration of the high heat flux in the device. The adverse thermal environment can seriously degrade the performance and service lives of electronic devices [1]. The advanced cooling technology is needed to solve the thermal problem of the electronic device. Heat pipe technology that utilizes the phase change latent heat of working fluid and transfers the high heat flux from hot side to cold side is expected to solve the thermal problem of electronic devices. In order to improve and strengthen the heat transport performance of heat pipes, finding out a suitable working fluid is one of the most direct and effective ways.

Self-rewetting fluids (SRWFs) are believed to improve the thermal performance of heat transfer devices. The concept of SRWF was raised by Abe et al. [2] in 2004, when they studied on the thermo-physical properties of the dilute aqueous solution of high carbon alcohols. SRWFs are non-azeotropic solutions satisfied to enjoy a particular surface tension behavior—an increase in the surface tension with increasing temperature. Due to the Marangaoni effect caused by the concentration gradient and the temperature gradient, the fluid spontaneously flows to the hotter region, justifying the expression of "self-rewetting" behavior, thus enhancing the heat transfer and preventing the dry out phenomenon of the heated surface. The interesting heat transfer enhancement behavior made the SRWF became the research hotspot. Suzuki et al. [3], Mcgillis and Carey [4] and Ahmed and Carey [5] pointed out that, compared with the water, twice or three times higher CHFs have been reported for SRWFs. With the aid of a two-wavelength interferometer and tracer particles, Abe et al. [2] observed the boiling behavior of the working fluids. The result qualitatively revealed liquid inflow to the nucleation site caused by coupled Marangoni effects in the SRWF. In order to show the anomalous behavior of SRWFs, Savino et al. [6] performed experiments in laboratory with Pyrex borosilicate glass capillary with inner diameter of 0.5 cm and length of 16 cm. The result showed that, for the SRWF, the evaporation region contained more liquid in comparison to water, which implies spontaneous liquid supply to the higher temperature region. All above, the SRWF can provide an additional force which moves the working fluid toward the hot region, and it is a promising working fluid used for the heat transfer device.

To confirm the heat transfer enhancement effect of the SRWFs, many researches on self-rewetting fluid heat pipes have been carried out. Especially in microgravity conditions or in the application

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of the microelectronic components, surface tension plays an important role on heat transfer enhancement. Aim at finding out the effect of SRWF on wick heat pipes, some experimental studies have been carried out. Savino et al [7–9] employed water and 0.1wt% heptanol aqueous solution as working fluids in the grooved heat pipes with diameter of 4 and 8 mm. In microgravity conditions, using water as working fluid, the both two grooved heat pipes dried out quickly. While the heat pipes using SRWFs showed much better thermal performance. Di Paola et al. [10] prepared self-rewetting nanofluids with single-wall carbon nanohorns as the working fluid of the grooved heat pipe. In microgravity conditions, the result showed that, heat pipe filled with self-rewetting nanofluids show better thermal performances. These results candidate self-rewetting nanofluids as an innovative working fluid for heat transfer application. Abe [11,12] tested the grooved heat pipes in the vacuum chamber, and the experiments were carried out in normal gravity condition at horizontal orientation. In the case of 4 mm heat pipes, the dry out limit of 1-butanol aqueous solution heat pipe was about 40% higher than the water heat pipe, and the thermal resistance was also reduced by 15%. In the case of 8 mm heat pipes, on the other hand, the reduction in the thermal resistance of 1-butanol aqueous solution heat pipe against water heat pipe was about 40%. Senthilkumar et al. [13,14] analyzed the thermal performance of heat pipes with stainless steel wick material, and they employed SRWFs and DI water as working fluid. The results showed that the heat pipes filled with SRWFs have more stable, higher thermal efficiency, and lower thermal resistance than heat pipe filled with water.

Through the above analysis, the SRWFs worked quite well in the wick heat pipes. Compared with the wick heat pipe, the wickless heat pipes can better exhibit the strengthen effect of the SRWFs, due to the lack of capillary structure. Furthermore, the requirement of external cycle power for wickless heat pipe is more pressing, and the influence of surface tension on wickless heat pipe is more intense. Therefore, the researches on the strengthen effect of the SRWFs on the wickless heat pipes were investigated. Abe [11,12] and Savino et al. [7,8] employed water and SRWFs as working fluids in the wickless copper heat pipes. Their results showed that, the wickless heat pipe with water dried out soon. As for the ones with SRWFs, the thermal resistance was decreased apparently, and the dry out limit has been improved. Tanaka et al. [15] fabricated ultra-light-weight wickless heat pipe panels with flexible, inflatable, and deployable functions using several different polyimide-based panel models. They conducted fundamental thermal performance tests under conditions of reduced gravity available in parabolic flight, and the result showed that the ultralight-weight wickless heat pipe panels with SRWFs as working fluids was successfully demonstrated and operated in low gravity. Fumoto et al. [16,17] performed a series of experiments to investigate the performance improvement resulting from the use of SRWFs in a pulsating heat pipe in vertical orientation. They pointed out that the use of SRWFs in a PHP was shown to be highly effective in improving the heat transport capability of pulsating heat pipes.

Overall, the heat transfer enhancement effect of SRWF is apparent, however, the enhancement mechanism in the micro heat pipe is not clear enough, and the research on the thermal performance of the micro oscillating heat pipe (MOHP) is inadequate. The MOHPs have the advantages of lightweight and miniaturization, but the heat transfer capability of the MOHP is hard to fulfill some specific requirement. For example, in horizontal orientation, the MOHP is insufficient to meet the cooling requirements. Therefore, using SRWFs as the working fluids of the MOHP is promising to improve the heat transfer capability, and expand the application range. In this paper, we focus on clarifying the heat transfer enhancement mechanism of MOHPs using SRWF. The thermo-physical properties (including surface tensions, contact angles and thermal conductivities) of SRWFs and deionized water have been comparatively analyzed. Furthermore, to find out the strengthening effect, experimental studies were performed on MOHPs with different sizes and different orientations (vertical and horizontal).

## 2. Experimental details

### 2.1. Working fluid thermo-physical properties

Selection of the working fluid for heat transfer applications depends on specific considerations. In order to distinguish the fluid thermo-physical properties between self-rewetting fluids (SRWFs) and common fluids, surface tension, contact angle and thermal conductivity have been measured through a series of laboratory research activities. The deionized water and 0.01 wt% to 0.1 wt% heptanol aqueous solutions were employed as the measurement samples.

#### 2.1.1. Surface tension measurement

The surface tension has been measured in the temperature range 20–80 °C with Dataphysics DCAT21 tensiometer using the Wilhelmy plate method. The temperatures of the samples remain stable through the temperature control system. After at least three times repeated measurements, the surface tension values were obtained at different temperatures. For each temperature, the maximum deviation was less than ±0.5 mN/m.

#### 2.1.2. Contact angle measurement

Contact angles have been measured for different liquids at room temperature 25 °C with the Dataphysics OCA20 video based optical contact angle measuring instrument, using the sessile drop method. During the measurement procedure, 5 μl measurement sample drops are placed on the copper foils with a syringe, and the angles are determined by taking a picture with a CCD camera and then measuring the contact angle of the water drop in the picture. Furthermore, the advancing and receding contact angle determinations by the needle-syringe method were also carried out on the same copper foils by using a stainless steel needle (outer diameter is 0.496 mm) connected with a microliter syringe. 9 μl samples were pushed out, while the three phase interline spread out, and the advancing contact angles were captured by the camera. After that, 9 μl samples were inhaled into the stringer, while the three phase interline fell back, and receding contact angles were captured. After repeated measurements, the measurements of contact angles could exhibit a repeatability of ±3°, and the advancing and receding angle values were obtained.

#### 2.1.3. Thermal conductivity measurement

The thermal conductivity of the samples was measured with the Hot Disk TPS 2500 thermal conductivity analyzer, using the transient plane source method at room temperature 25 °C. The values of the thermal conductivity of the samples can be read in the computer. The measurement error was controlled within ±5% after repeated measurements.

### 2.2. Experimental apparatus and procedures

To find out the enhancement effect of the SRWF in micro oscillating heat pipes, copper tubes with inner diameter ($D_i$) of 0.4, 0.8, and 1.3 mm were used as manufacturing material, and they were welded into the four-turn MOHPs separately. The heat transfer length ($L$) of 100, 150 and 200 mm were adopted for comparative experiments. The deionized water and 0.1wt% heptanol aqueous solutions were employed as the working fluids during the