Capillary-assisted evaporation of water from finned tubes: Impacts of dynamics and experimental setups

Author(s):
Seiler, Jan; Volmer, Rahel; Krakau, Dennis; Pöhls, Julien; Ossenkopp, Franziska; Schnabel,Lena; Bardow, André

Publication date:
2020-08

Permanent link:
https://doi.org/10.3929/ethz-b-000459644

Originally published in:
https://doi.org/10.18154/RWTH-2020-10192

Capillary-assisted evaporation of water from finned tubes: Impacts of dynamics and experimental setups

Seiler, Jan[1], Volmer, Rahel[2], Krakau, Dennis[1], Pöhls, Julien[2], Ossenkopp, Franziska[2], Schnabel, Lena[2] and Bardow, André[1,3*]

[1] *Institute of Technical Thermodynamics, RWTH Aachen University, 52062 Aachen, Germany*

[2] *Department Heating and Cooling Technologies, Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstr. 2, 79110 Freiburg, Germany*

[3] *Institute of Energy and Climate Research (IEK-10), Forschungszentrum Jülich, 52425 Jülich, Germany*

[4] *Energy & Process Systems Engineering, ETH Zurich, 8092 Zürich, Switzerland*

[*] *Corresponding Author: abardow@ethz.ch*

Abstract:
Capillary-assisted thin-film evaporation has attracted increased attention recently to efficiently evaporate the natural refrigerant water at low pressures. Although capillary-assisted evaporators have been studied in many publications, it remained unclear if published results can be compared. Respective measurements are often conducted under different conditions in terms of setup, procedure and evaluation, and potentially important factors are not specified or disregarded. In this work, we compare experimental setups and procedures. Experiments with finned copper tubes are conducted at RWTH Aachen and Fraunhofer ISE. A set of requirements is identified to ensure good agreement of the overall heat transfer coefficients. Major requirements are the specification of the heat exchanger's surface properties, analysis of measurement uncertainty, well-specified input conditions, and control of non-condensable gases (NCG). Furthermore, dynamic experiments with continuously decreasing filling levels prove to be well-suited to quickly assess the heat transfer at all filling levels in a single experiment. Thus, this work identifies approaches for fast, reproducible and comparable characterization of capillary-assisted evaporation.

1 Introduction

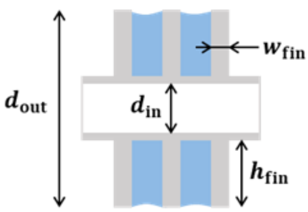
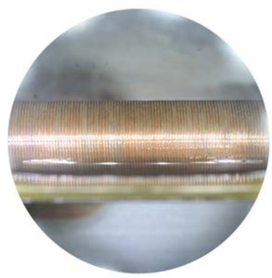
Due to its environmental friendliness, broad availability and high enthalpy of evaporation, water is often used as refrigerant in thermally driven heat pumps. However, low-pressure evaporation of water at low temperatures is challenging since the favourable nucleate boiling regime can only be achieved by high superheats [1] which can usually not be provided in thermally driven heat pumps. To overcome this drawback, capillary-assisted thin film evaporation has been intensively investigated recently [2-6]. However, published measurement results occasionally differ strongly in their underlying experimental setup, instrumentation, procedures, and definition of evaluation quantities. So far, it has not been investigated to what extent these factors affect measurement results and thus if published results are comparable.

In this work, we investigate if capillary-assisted evaporation is affected by the experimental procedure (decreasing vs. constant filling levels) and by experimental setups (setup A at RWTH[1] vs. setup B at ISE[2]). We identify requirements for obtaining comparable results. Contents of this work have also been published in [7].

2 Experimental setup and data reduction

The geometry of the investigated finned copper tubes (Table 1) was chosen to create strong capillary action for thin-film evaporation. An internal structure of the tube prevents limitations of the overall heat transfer coefficient on the inside.

Table 1 – Details of finned tube investigated in this work.

Tube property	Value	Sketch of tube	Tube in setup
Material	Cu (C12200)		
Tube inner diameter d_{in}	9.6 mm		
Tube outer diameter d_{out}	13.2 mm		
Fin spacing	56 fpi		
Fin width w_{fin}	0.15 mm		
Fin height h_{fin}	0.8 mm		
Tube inner fluid side	Internal structure		
Total length of tubes L	2 m		

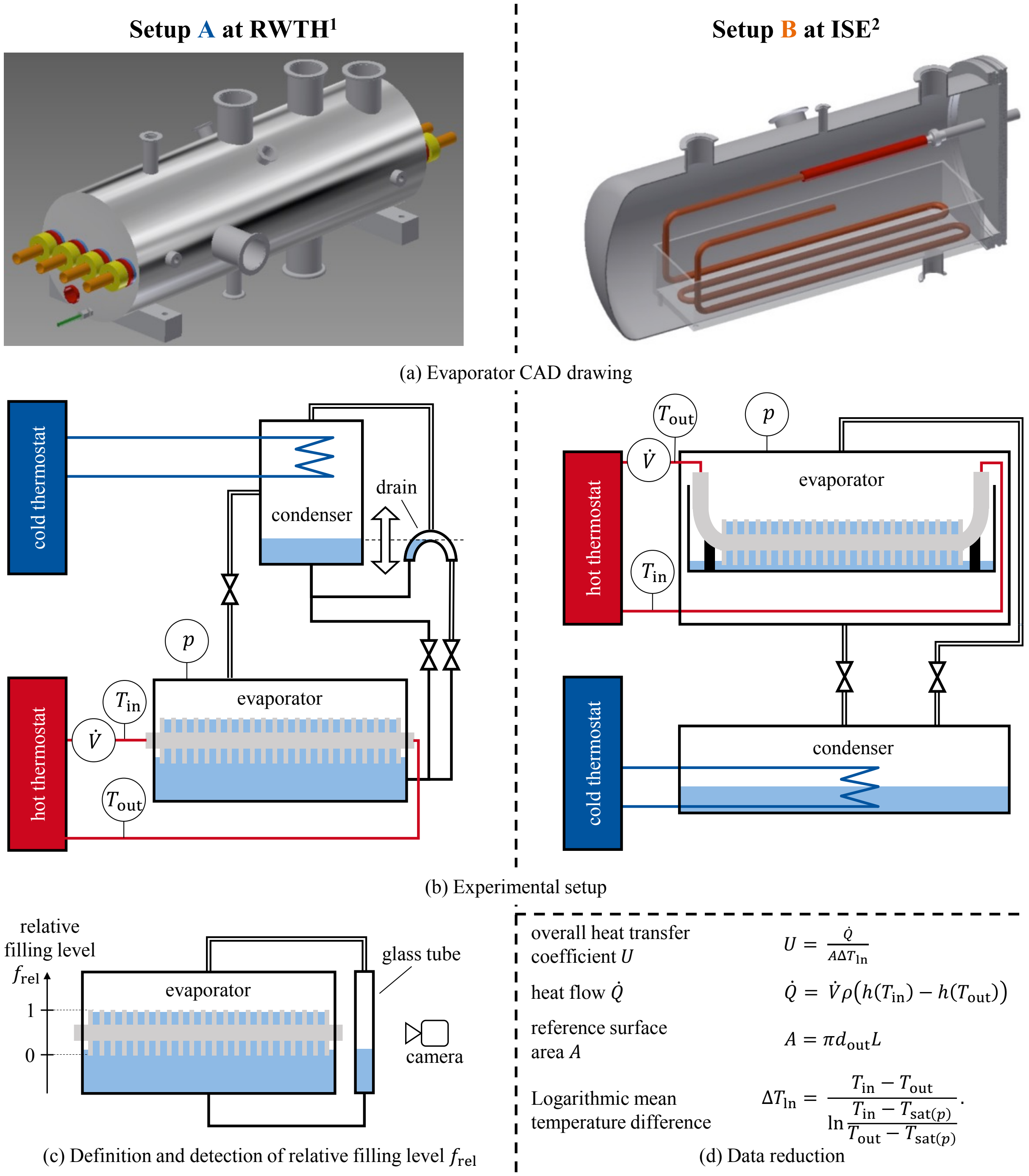


Figure 1 – Employed experimental setups A (left) and B (right). (a) CAD drawing of evaporator chambers with installed finned tubes. (b) Sketches of experimental setups with installed sensors for temperature (T), volume flow rate ($\dot{V}$) and pressure (p) in evaporator and condenser. (c) Definition and detection of relative filling level in communicating pipe of experimental setup A. (d) Data reduction which is identical for both setups. Refrigerant and secondary fluids are water and its physical properties (density ρ, specific enthalpy h and saturation temperature T_{sat}) are calculated by RefProp using the equation of state "IAPWS-95" [8].

Four identical tubes were serially connected and installed in the vacuum-tight evaporator chambers in the experimental setups A and B. Details of the similar setups along with the employed data reduction are given in Figure 1. The setups differ in condenser (type and position), the way the refrigerant is supplied to the evaporator (liquid reflux in setup A vs. condensed in setup B), connection of the tubes (outside in setup A vs. within vacuum chamber in setup B) and the measurement uncertainty of the used sensors [7].
Both setups measure at decreasing filling levels, thereby determining the overall heat transfer coefficient U at all filling levels within a single experiment. Additionally, the setup A also allows experiments at any constant filling

level in steady-state condition. The desired constant filling level in the evaporator can be changed by adjusting the height of the drain without affecting the vacuum in the experimental setup (cf. Fig. 1 (b), left). A camera and an image analysis algorithm automatically determine the filling level. Knowledge of the uncertainty of the conducted measurement is important for the evaluation of low-pressure evaporation. Therefore, the whole measurement chain including data reduction was analysed regarding uncertainty u according to GUM [9] with the “law of propagation of uncertainty” for uncorrelated input quantities x_i

$$u_{f(x_i)} = \sqrt{\sum_i \left(\frac{\partial f}{\partial x_i}\right)^2 u_{x_i}^2} \tag{1}$$

using a coverage factor of $k = 1$. The calculated uncertainties for the U–values are shown in Figure 3.

2.1 Experimental procedure

The following experimental procedure was employed to ensure comparable experiments: Since surface condition affects wetting of the tubes [7], the tubes were cleaned with isopropanol before installation. The refrigerant was degassed, deionized/bi-distilled water. Control of non-condensable gases (NCG) dissolved in the refrigerant or attached to surface is crucial since NCGs affect condensation, evaporation and the evaluation of the saturation temperature by pressure measurement. Thorough evacuation after the installation of the tubes (until experimental results did not change anymore) and additional evacuation prior to (in setup B) or during (in setup A) each experiment ensured no impact from NCGs. Before the experiments started, the tubes were submerged in refrigerant to fully wet their surface. The thermostats were set to constant inlet conditions (cp. boxes in Figure 2 and Figure 3). The inlet conditions of the condenser were set to obtain identical pressure in the evaporation chamber during the experiment. Measured inlet conditions were identical within uncertainty of measurement during all experiments [7].

3 Results

3.1 Impact of dynamics - decreasing vs. constant filling levels

In Figure 2, the results for experiments with decreasing filling level versus 6 constant filling levels and identical inlet conditions (given in blue box in the figure) are presented. Reproducibility of both types of experiments is very good. Although measured U–values at constant filling levels are generally 5-10 % lower than measured U–values at decreasing filling level, they mostly coincide within uncertainty of measurement. Detachment occurs at

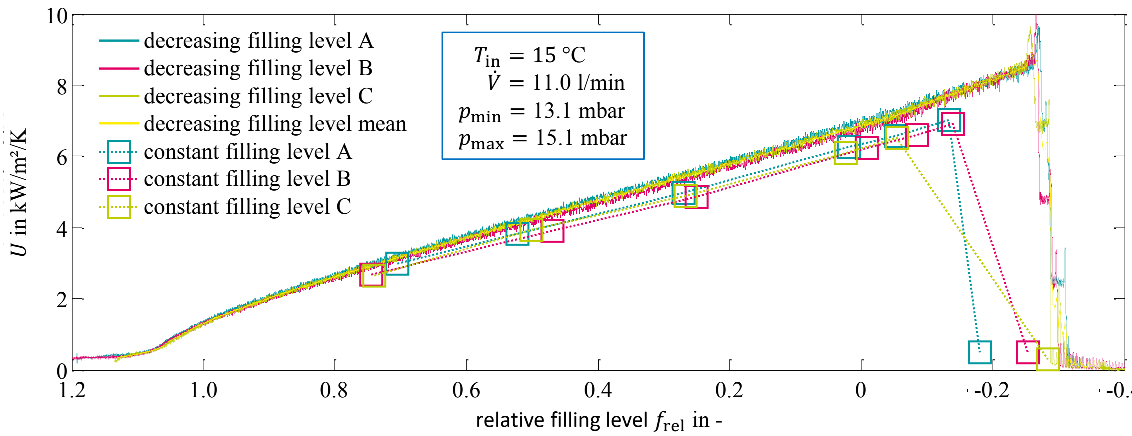


Figure 2 – Overall heat transfer coefficient U for decreasing and constant filling levels in setup A.

higher f_{rel} for constant filling levels, which is probably caused by difficulties to precisely set low constant filling levels due to a meniscus in the drain. Since the menisci between the tubes and the refrigerant in the evaporator are very fragile at filling levels below the tube, these filling levels will probably not be used in real-world applications anyway. Thus, experiments with decreasing filling levels are well-suited to quickly assess the U–values at all filling levels in a single experiment. Furthermore, operating capillary-assisted thin-film evaporator with decreasing filling levels might enhance the U–value by up to 10 %.

3.2 Impact of experimental setups

In general, the results in setups A and B are very similar (Figure 3). For low driving force (low ΔT_{ln}, Figure 3, left), the measured U–values coincide within uncertainty of measurement, while the measured U–values differ up to 24 % for high driving forces (Figure 3, right). Overall, the agreement of the experiments is very good and shows that obtaining comparable results with different experimental setups is possible. The remaining difference can be explained by 3 effects: (1) Capillary action might have deteriorated due to altered surface properties of the tubes in setup B caused by necessary brazing for vacuum-tight connection of the tubes. (2) The configuration of the refrigerant pool differs in setup A and B (Figure 1): in setup A, the evaporator contains more refrigerant which is also thermally connected to the metal vessel. Therefore, its thermal mass is increased which leads to comparably lower evaporating temperatures in setup B which in turn lead to lower U–values. (3) Unknown measurement uncertainties and/or distorting effects could also have caused the observed differences.

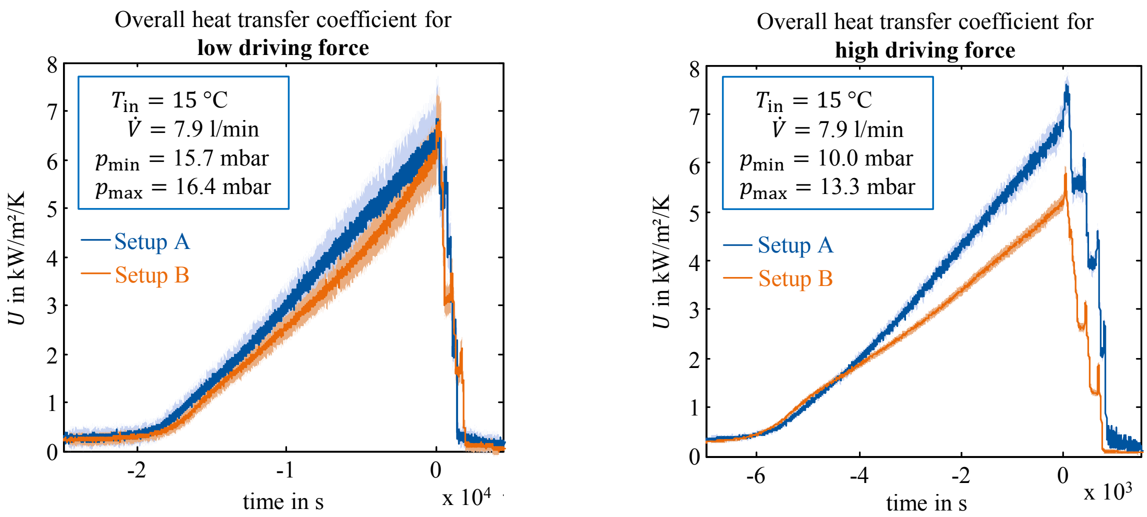


Figure 3 - Overall heat transfer coefficient U shown with uncertainty (as shade in light colour in the background) plotted over time for decreasing filling levels for low driving force (left) and high driving force (right). As can be seen in both plots, measurement uncertainty is lower at high driving force (right), yet similar in both setups (A and B). Both experiments (in setups A and B) are synchronized at the end of the experiment (t=0) when the first tube loses contact to the refrigerant pool.

4 Conclusions

The results demonstrate that experiments with continuously decreasing filling levels are well-suited to quickly assess the U–values at all filling levels in one single experiment. Furthermore, experiments in two different setups A and B can produce identical results within uncertainty of measurement. The following aspects should be considered to ensure reproducible and comparable experiments of capillary-assisted thin-film evaporation: (1) exact definition of the investigated heat exchangers' surface properties is important; (2) analysis of uncertainty of measurement and accordingly choice of appropriate sensors and design of experiment; (3) input conditions need to be identical and if possible constant; and (4) vacuum tightness and control of NCGs are crucial for reproducibility. Our work indicates that measurement results from different laboratories probably allow for a good comparability if the stated aspects are taken into account.

5 Acknowledgment

We thank Wieland Werke AG for providing the heat exchanger tubes. RWTH Aachen and Fraunhofer ISE gratefully acknowledge the financial support from the German Federal Ministry for Economic Affairs and Energy BMWi) in the "7th Energy Research Programme of the Federal Government" (03EN2002A & 03EN2012A). The work at Fraunhofer ISE was supported by Fraunhofer Zukunftsstiftung in the context of the project HArVest.

6 List of References

[1] Giraud, F., Rullière, R., Toublanc, C., Clausse, M., Bonjour, J. (2015): Experimental evidence of a new regime for boiling of water at subatmospheric pressure. *Exp. Therm. Fluid Sci.,* vol.60, pp.45–53.

[2] Seiler, J., Lanzerath, F., Jansen, C., Bardow, A. (2019): Only a wet tube is a good tube. *Appl. Therm. Eng.*, vol.147, pp.571–578.

[3] Volmer, R., Eckert, J., Füldner, G., Schnabel, L. (2017): Evaporator development for adsorption heat transformation devices. *Renew. Energy*, vol.110, pp.141–153.
[4] Thimmaiah, P.C., Sharafian, A., Huttema, W., Osterman, C., Ismail, A., Dhillon, A., Bahrami, M. (2016): Performance of finned tubes used in low-pressure capillary-assisted evaporator of adsorption cooling system. *Appl. Therm. Eng.*, vol.106, pp.371–380.
[5] Lanzerath, F., Seiler, J., Erdogan, M., Schreiber, H., Steinhilber, M., Bardow, A. (2016): The impact of filling level resolved. *Appl. Therm. Eng.*, vol.102, pp.513–519.
[6] Xia, Z. Z., Yang, G. Z., Wang, R. Z. (2008): Experimental investigation of capillary-assisted evaporation on the outside surface of horizontal tubes. *Int. J. Heat Mass Transf.*, vol.51, pp.4047–4054.
[7] Seiler, J., Volmer, R., Krakau, D., Pöhls, J., Ossenkopp, F., Schnabel, L., Bardow, A. (2020): Capillary-Assisted Evaporation of Water from Finned Tubes. *Appl. Therm. Eng.*, vol.165, 114620.
[8] Wagner, W., Pruß, A. (2002): The IAPWS Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use. *J. Phys. Chem. Ref. Data*, vol.31, pp.387-535.
[9] Joint Committee for Guides in Metrology (2008): Evaluation of measurement data - Guide to the expression of uncertainty in measurement (GUM). http://www.bipm.org/en/publications/guides/gum_print.html