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Measurement of Radiative Transport Properties of Water and Refrigerant R245fa

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ABSTRACT

Infrared (IR) thermography could significantly contribute to advancing our comprehension of heat transfer phenomena, particularly in the field of nuclear engineering. It enables the non-intrusive experimental study of various heat transfer processes, including flow boiling. However, with thermography, an accurate determination of radiative heat transfer properties is of vital importance to yield reliable results. Methods for assessing gas-liquid interface emissivity and fluid transmissivity are introduced. Both approaches utilize an IR camera sensitive to longwave IR radiation in wavelengths 7.5–13 μm. The emissivity evaluations were conducted within temperature range of 30–80 °C. The water surface emissivity of 0.89 ± 0.09 has been measured, when surface temperature is at least 5°C above ambient conditions (24 ± 1°C, 100 ± 0.1 kPa). The accuracy of measurement technique was validated through comparison with data from literature. Transmissivity measurements indicated that both liquid water and R245fa lack adequate IR radiation transparency within the examined spectrum to enable the observation of heat transfer mechanisms around a hot object submerged in flow.

1 INTRODUCTION

Understanding heat transfer phenomena is crucial from a fundamental physics perspective and for ensuring the safety and reliability of Nuclear Power Plants (NPPs) [1]. Beyond its relevance in nuclear systems, heat transfer plays an important role in a range of other sectors, including computer cooling systems, medical industry, oil industry and various manufacturing processes [2]. Given the complexity of heat transfer mechanisms, there is a critical demand for rigorous and innovative approaches to their study, analysis, and practical application [3]. This need is elevated in the context of multiphase flows involving phase change, such as flow boiling phenomena, which constitutes a primary area of research focus in the THELMA laboratory of Reactor Engineering Division, *"Jožef Stefan"* Institute, Slovenia [4].

Experimental observations serve as an essential foundation for investigating multiphase flow phenomena. Two primary methods can be categorized for observing such flows: intrusive and non-intrusive techniques. The intrusive methods display a significant limitation – an introduction of sensors into the flow field may act as a perturbation, potentially altering the inherent characteristics of the flow and associated heat transfer mechanisms. In contrast, non-intrusive techniques provide the advantage of allowing for observation without direct contact with the flow. This ensures that the original flow conditions remain undisturbed, facilitating a more accurate representation of the underlying mechanisms [5].

Among non-intrusive technologies, Infrared (IR) thermography emerges as a particularly effective instrument for the study of heat transfer phenomena. IR thermography facilitates the direct measurement of heat fluxes at the source, thereby providing valuable data for understanding underlying mechanisms [6]. However, the accuracy of IR thermography depends upon a thorough understanding of radiative transport properties. Proper calibration and in-depth knowledge of these properties are prerequisites for obtaining reliable measurements. A lack of such understanding may introduce significant inaccuracies in both observational data and subsequent interpretations [7].

In the present study, we examined the applicability of IR thermography for investigating flow boiling phenomena. The experimental setup predominantly utilizes water and R245fa refrigerant as working fluids in temperature range from about 30 to 80 °C. The broader objective of our work is to observe boiling processes adjacent to the heated surface via an IR-transparent window, employing an IR camera for observations. Two critical radiative transport properties integral to this methodology are the emissivity of the gas-liquid interface and the transmissivity of the liquid. Specifically, emissivity quantifies the efficiency with which the surface emits thermal radiation, and transmissivity describes the inherent property of the fluid that allows electromagnetic radiation to pass through it [7]. Accurate understanding of these properties is crucial for obtaining reliable measurements of temperature fields and heat flux.

2 EXPERIMENTAL SETUP AND METHOD

2.1 Gas-Liquid Interface Emissivity Measurement

The measurement system is comprised of an IR camera (FLIR X6901sc SLS) [8], a T-type thermocouple [9], and a black container featuring an aluminium bar, a diffuse reflector, and liquid working fluid. The system is depicted in Figure 1.

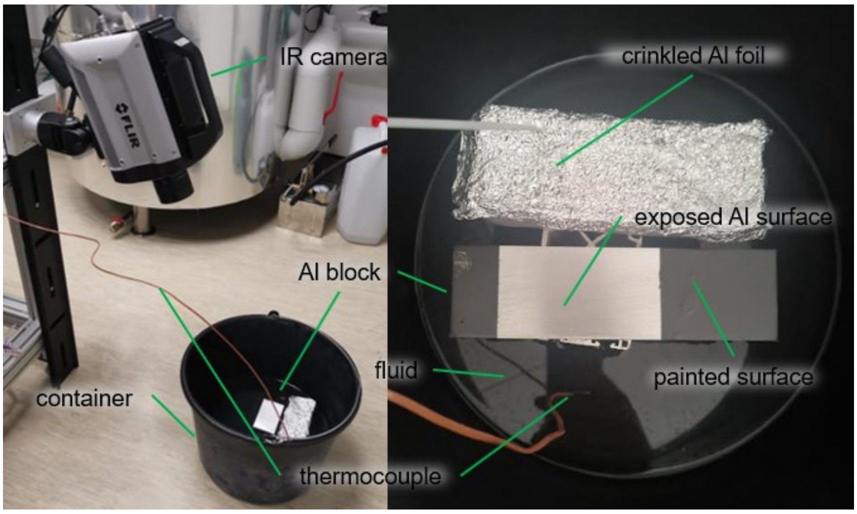

Figure 1: Measurement system for determination of gas-liquid interface emissivity with detailed representation of container contents (experimental campaign water III)

A region of the aluminium bar painted black served as a reference surface with a known emissivity. The brushed aluminium surface was utilized for cross-comparison of our results with the known surface emissivity from literature, serving to validate the measurement method. A crinkled aluminium surface was used as an approximation for the diffuse reflector, which serves as an estimate for the background IR radiation from the environment.

The infrared camera was positioned at an angle of 30–45 ° relative to the normal of the water surface, which mitigates the reflection of the camera lens in the captured images. Strained Layer Superlattice (SLS) sensor in the IR camera is sensitive to radiation with wave lengths of 7.5–13 μm.

The assumed emissivity for the acrylic matte paint applied to the reference surface was 0.95 [10]. Surface preparation of the aluminium specimen involved the use of P150 and P180 sandpaper corresponding to surface roughness Ra of 1.06 and 0.76 μm, respectively [11]. Measurements were conducted over a temperature range from 30 °C to 80 °C. The ambient temperature and pressure were kept constant at 24 ± 1°C and 100 ± 0.1 kPa, respectively.

The measurement procedure was initiated with the system containing hot fluid, which was gradually cooled down to ambient temperature. This method facilitated the determination of emissivity across the entire temperature range of interest and enabled the calculation of error propagation.

Two types of measurement data were collected: the IR image – intensity of IR radiation (in unit [counts]) and the temperature (in unit [°C]) as recorded by a thermocouple via NI PXIe-4353 [12] data acquisition system. The thermocouple was referenced to the Kaye-170e artificial triple point of water [13]. The sampling frequency was set at 0.033 Hz ($\approx 2\ \mathrm{min}^{-1}$), which is adequately suited for capturing the dynamics of the observed process. Four measurement campaigns were conducted with water and one with R245fa, with each lasting about 5–6 hours and 1 hour, respectively.

Calculation of emissivity and measurement error

The radiation captured by an IR camera includes emitted, transmitted, and reflected infrared light originating from both the object and its surroundings. For opaque surfaces, which do not permit light transmission, the recorded radiation consists only of emitted and reflected light [7]. In this case, the calculation of emissivity is based on IR measurements from a single object maintained at a uniform temperature but featuring two (or more) distinct surface emissivities. Specifically, the known emissivity of acrylic paint, denoted as ε_{BL}, is 0.95 [10], while the unknown emissivity of other objects or fluid surface is denoted as ε_{UN}. The captured IR radiation of black painted surface R_{BL}^* and unknown object R_{UN}^* can be described as [7]:

$$R_{BL}^* = \varepsilon_{BL} R_{BL} + (1 - \varepsilon_{BL}) R_{ENV}^* \ , \tag{1}$$

$$R_{UN}^* = \varepsilon_{UN} R_{BL} + (1 - \varepsilon_{UN}) R_{ENV}^* \ , \tag{2}$$

where R_{ENV}^* is measured ambient IR radiation, represented by a diffuse body. By solving a system of equations, the formula to determine the unknown emissivity ε_{UN} can be derived:

$$\varepsilon_{UN} = \varepsilon_{BL} \frac{R_{BL}^* - R_{ENV}^*}{R_{UN}^* - R_{ENV}^*}. \tag{3}$$

Values of R_{BL}^*, R_{ENV}^* and R_{UN}^* have been determined with IR image postprocessing software FLIR ResearchIR [14] as mean values of counts in each subdomain of the captured image (see Figure 2).

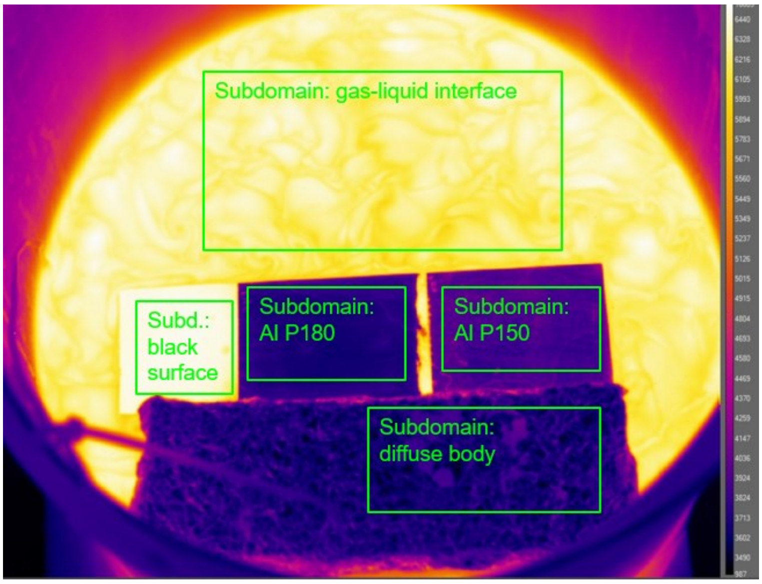

Figure 2: Captured IR image with subdomains (experimental campaign water IV)

Given the presence of various uncertainties, it is essential to compute error propagation for an accurate interpretation of the calculated values. For the emissivity of paint, the range of values found in the literature varies between 0.90 and 0.95 [15]. Consequently, a symmetrical absolute error of 0.05 was assumed for the paint emissivity, denoted as σ_ε. For the count number error, the standard deviation (σ^*_{BL}, σ^*_{ENV} and σ^*_{UN}) of counts in each image subdomain was utilized. Relative error of the calculated surface emissivity δ_{UN} was obtained using formula:

$$\delta_{UN} = \frac{\sigma^*_{BL}+\sigma^*_{ENV}}{R^*_{BL}-R^*_{ENV}} + \frac{\sigma^*_{UN}+\sigma^*_{ENV}}{R^*_{UN}-R^*_{ENV}} \pm \frac{\sigma_\varepsilon}{\varepsilon_{BL}} \tag{4}$$

2.2 Fluid Transmissivity Measurement

Determining the transmissivity of a fluid presents inherent challenges due to very low transparency of practically all liquids in IR spectrum. Conventional methods often forgo the use of an IR camera and instead measure the heat flux from IR radiation source to submerged object with known high emissivity (acting as an IR detector). This is usually accomplished by recording the temperature at gas-liquid interface and at the surface of an immersed black object upon which the IR source is radiating, utilizing fast-response thermocouples. The amount of transferred radiation is subsequently calculated based on the acquired temperature data [6].

In contrast, our study aimed to assess the feasibility of measuring fluid transmissivity using an IR camera, with a specific emphasis on measuring the temperature of a hot object submerged in a fluid. The measurement system used included an IR camera, an IR source, a containment box with an IR-transparent windows, and a T-type thermocouple to monitor the temperatures of both the fluid and the IR source. Fluids were contained within the box at ambient temperature for water and saturation temperature for refrigerant (~15.3 °C). The system is depicted in Figure 3-a.

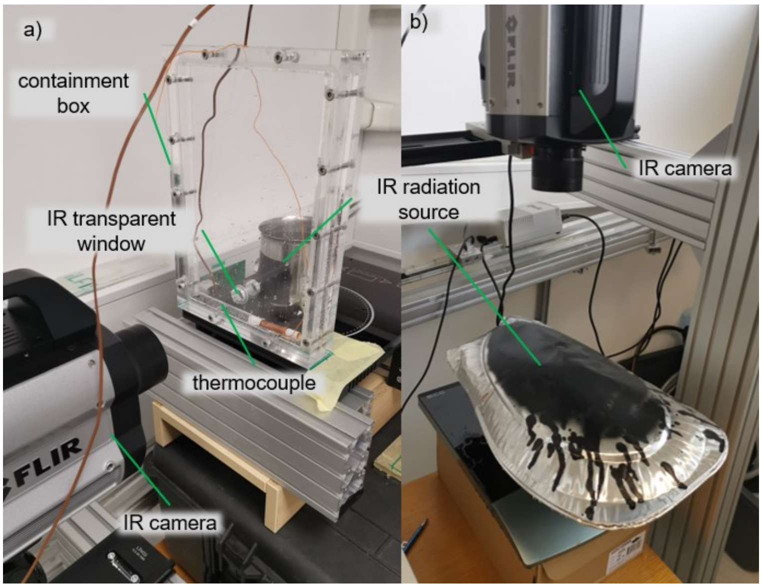

Figure 3: Measurement system for determination of transmissivity of fluid: original system (a) and the modified system (b).

The transmissivity of a very thin film of fluid was also measured. Modifications were made to the existing measurement system to enable fluid to be dripped onto the IR-transparent window. The modified system (absent a containment box) is depicted in Figure 3-b.

A container filled with the boiling water, which was constantly heated to maintain its boiling state, served as the source of IR radiation. This approach provided a stable radiation source with a constant temperature of 98 ± 1°C. To enhance the radiation characteristics, a thin layer of acrylic black paint was applied to the container's surface. The uniformity of the IR radiation emitted from the utilized source is illustrated in Figure 4-a for original system and in Figure 4-b for modified system. Transmissivity properties of IR-transparent window in containment box are shown in the Figure 5-a for original system and in Figure 5-b for modified system.

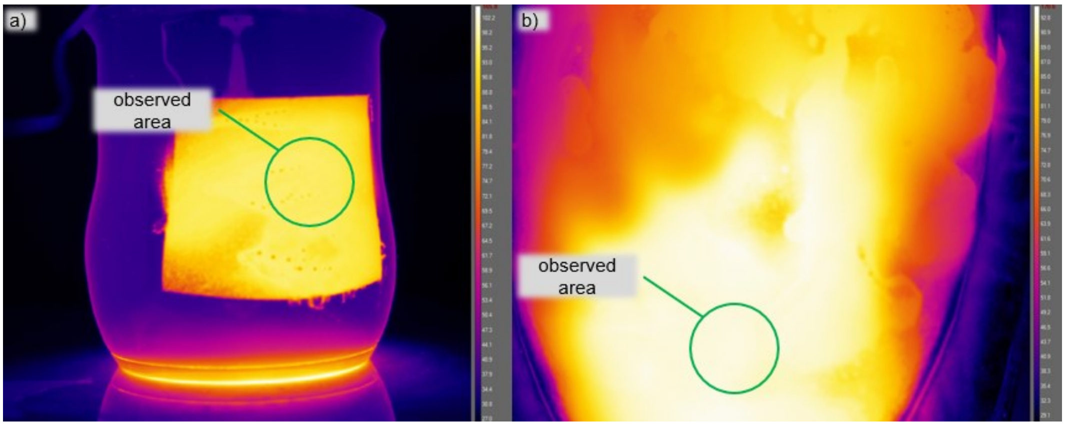

Figure 4: Uniformity of the IR radiation from source

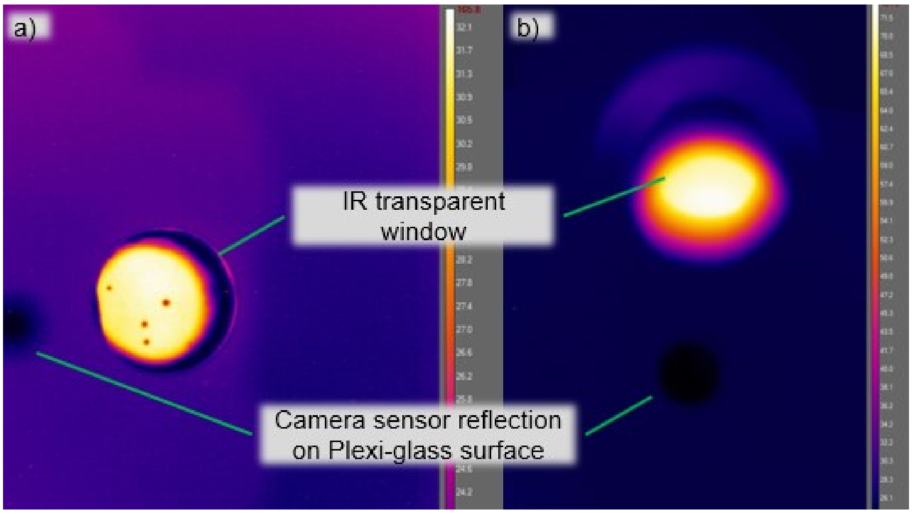

Figure 5: Transmissivity properties of IR-transparent window in containment box

3 RESULTS

3.1 Gas-Liquid Interface Emissivity

The emissivity values of water-air interface stabilize around a range of 0.89 ± 0.09 when the temperature is about 10°C above ambient conditions. More detailed outcomes of the emissivity measurements at the water-air interface are displayed in Figure 6, which compiles data from all four experimental campaigns. Error estimation is restricted to Campaign IV, as methodological improvements in this stage give us greater confidence in these results. For Campaign IV, emissivity measurements for the aluminium surface, subjected to two distinct treatments, are also provided. This campaign was conducted down to a temperature limit of approximately 35 °C due to the significant impact of ambient radiation at lower temperatures, which negatively influences the quality of the measurements (as noted in Campaigns I, II, and III).

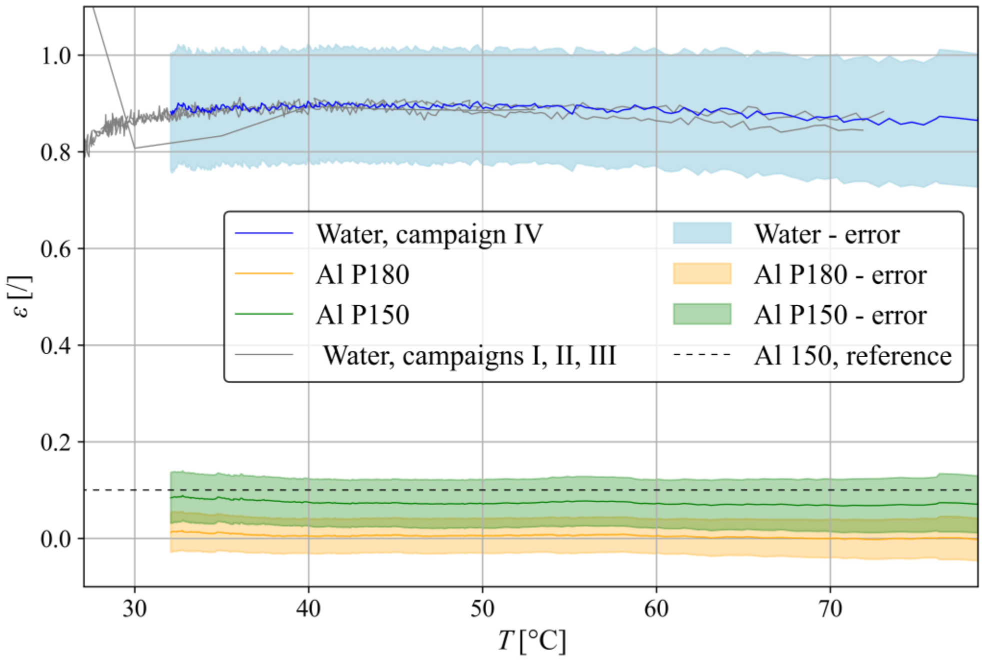

Figure 6: Measured emissivity of water-air interface and aluminium surface in observed temperature range

To assess the method's validity, the measured emissivity for an aluminium surface with an estimated roughness of Ra 1.06 μm (P150) was compared with data available in the literature [16], which is depicted in Figure 7. Surface treatment proves to be a key variable; most published research suggests an emissivity value of approximately 0.07 for a rough surface and 0.18 for a semi-polished surface [15]. Our data aligns well with these literature values. Moreover, a comparison between different campaigns confirms the repeatability of the results, further validating the appropriateness of the measurement method.

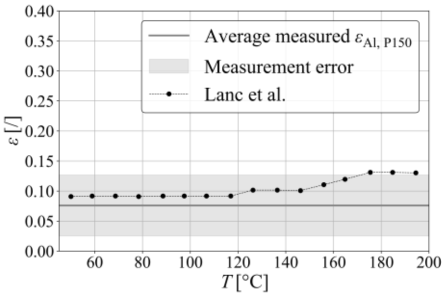

Figure 7: Emissivity of Al surface with roughness Ra 1.06 μm – comparison with the literature [16]

The existing conditions at ambient pressure limited our investigation to the properties of water. For measurements with R245fa an environment should be pressurised or cooled to at least 4 °C to reduce the influence of ambient radiation and prevent boiling of the fluid (saturation temperature 15.3 °C). Given our current equipment limitations, tests involving R245fa were not conducted. Therefore, measuring the emissivity of R245fa remains a focus for future research.

3.2 Fluid Transmissivity

The outcomes of the transmissivity assessments for water and R245fa refrigerant using the proposed method indicate that transmissivity cannot be ascertained for these fluids, as they transmit minimal IR radiation. This is further corroborated by Figure 8, which depicts the IR images captured both in the original system arrangement and in an adapted set-up designed to measure the transmissivity of a 1–3 mm thick fluid film. Data for both water and R245fa refrigerant are included.

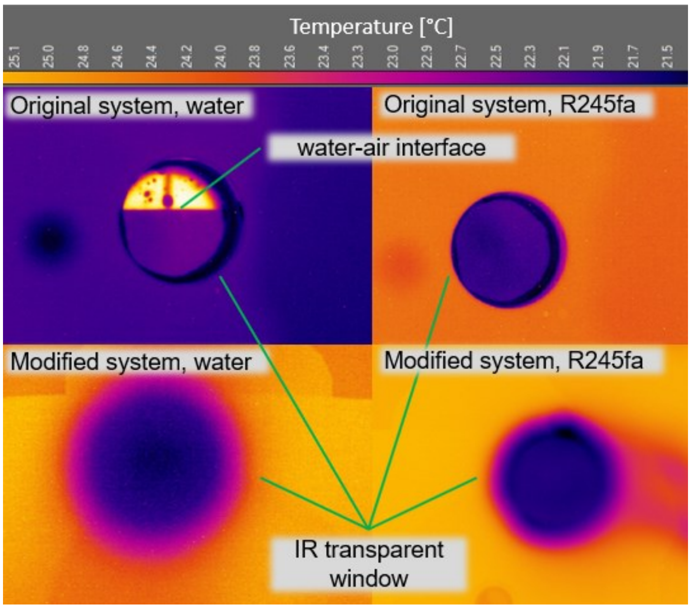

Figure 8: Results of the transmissivity measurements

As a result, the methodology initially delineated in the introductory chapter proves inadequate for calculating the transmissivity of these fluids. Such a constraint makes the application of an IR camera for flow boiling experiments incompatible with the approach originally set forth.

4 CONCLUSION

The study evaluated a measurement method for quantifying the emissivity of a gas-liquid using an IR camera and thermocouples. This approach was applied to two working fluids, water and R245fa refrigerant, which are used in the THELMA laboratory of Reactor Engineering Division, Jožef Stefan Institute. The adequacy of this method was confirmed by comparing our measurements with reference values from the literature. Our findings indicate commendable repeatability, recording surface emissivities of 0.89 ± 0.09 in the temperature range 30–80 °C for water interface. Measurements within ~5°C above the ambient temperature exhibit significant, unreliable measurement errors and should not be trusted. The same approach would have been suitable for evaluating the surface emissivity of R245fa refrigerant; however, the limitations of high ambient temperatures made the measurements unfeasible, due to low boiling point of the fluid.

The method initially proposed falls short in determining the transmissivity of the fluids under study, owing to their limited ability to transmit IR radiation. This presents a notable hindrance when considering the utilization of longwave IR cameras for investigation of heat transfer mechanisms around a hot object submerged in fluid flow. This important finding should be considered when planning future experimental work. The search for a better method to determine transmissivity therefore remains to be left for our future research.

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DECLARATION OF GENERATIVE AI IN THE WRITING PROCESS

During the preparation of this work the authors used Chat GPT-4 in order to improve readability and language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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