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Investigation of immersion media and materials for optical diagnostics in curved wall channels by the matching index of refraction

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Abstract. Five different refractive liquids and two possible transparent solid materials were tested to perform matched index of refraction (MIR) optical flow measurements and visualisation in channels with curved walls, for example, models of rods in fuel assemblies. The results of the tests showed that the selection of refractive liquid is always a compromise between effective and sometimes hazardous substances such as p-Cymene or essential oils and their less harmful substitutes with higher dynamic viscosity, such as white mineral oil.

1 Introduction

Optical diagnostic methods are widely used for studies of hydrodynamics and heat and mass transfer models of flow parts of energy equipment due to the fact that they do not disturb the flow. The use of the methods is limited by the presence of complex curved interface surfaces of media with different refractive indices that promote optical distortions. The use of liquids with a high refractive index, close to the optical characteristics of the transparent material of the model, can significantly reduce distortion [1].
Working with standard highly refractive liquids is not always convenient and safe for the researcher. Some of the solutions are toxic, such as methylene iodide, or are not optically stable like solutions of metal iodide salts, or they are flammable, and many also have a persistent specific odor [2].

For the application of immersion solutions as a liquid medium in hydrodynamic setups, it is important to know their physical properties, such as density and viscosity, as well as the dependence of the refractive index and viscosity on temperature and concentration [3].
In this paper, variants of immersion solutions based on NaI, aroma hydrocarbons and mineral (white) oil are investigated for optical diagnostics of velocity fields in internal subchannels between rod models in fuel assemblies [1, 2].

2 Methods and materials used

The refractive index (RI) of transparent solutions and substances was measured using the Abbe refractometer IRF-22, which was thermostatically controlled ±0.1C by a liquid

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thermostat LOIP FT-311-25 at a certain temperature. RI of acrylic and quartz tubes was tested using α-bromonaphthalene RI fluid oil. The uncertainty of the measurement of the refractometer according to the technical characteristics is ±2*10^{-4}. The refractometer was calibrated with a known RI test sample before measurements at the upper end of the scale and the accuracy of calibration with distilled water was checked at the lower end.

Thermally controlled rotational rheometer RheolabQC was used for dynamic viscosity measurements. All measurements were carried out with a change in the shear rate from 10 to 1200 1/s, a total of 50 points.

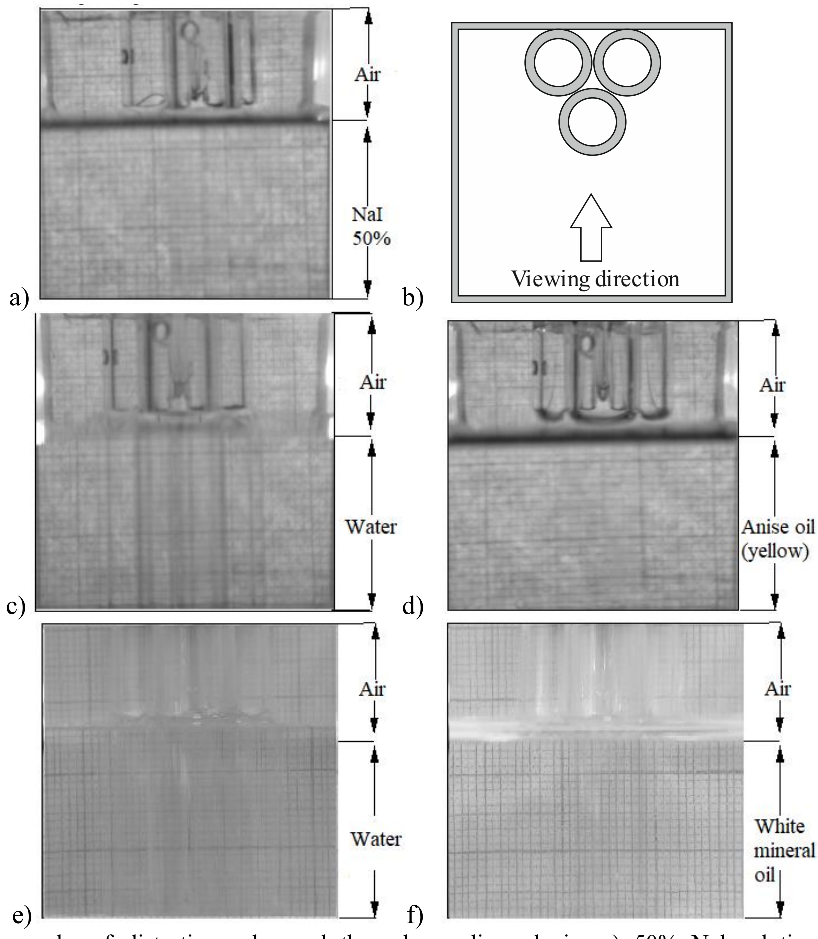

Fig. 1. Photographs of distortions observed through acrylic rods in: a) 50% Nal solution, b) observation diagram top view, c) water, d) anise oil (yellow); quartz rods in: e) water, f) white mineral oil.

3 Results and analysis

The results of visualisation of optical distortions when viewed from the side of three stacked acrylic and quartz rods in various liquids are presented in Figure 1.

The results of the RI and dynamic viscosity measurements for transparent liquids are presented in Table 1. We started testing with the 50% NaI water solution that was used in our previous experiments. The salt has a low viscosity and an acceptable refractive index when dissolved in an appropriate proportion in water. However, it has a major drawback linked with its lifetime of the matching liquid, as it is unstable under daylight and can crystallise with dark brown colour deposition on walls due to the iodine content. The next frequently used refractive index matching fluid is p-Cymene, which is suitable for matching with acrylic tubes (see Table 2 with the corresponding properties of the transparent rod models) as the sodium iodide solution does. One of the difficulties of p-Cymene aromatic organic compound is its toxicity with a specific intense odor and the increased flammability potential of its vapor. Two essential oils of aniseed with a high and low degree of purification were also tested following the paper [1]. Although the highly purified sample of the transparent anise oil had perfect viscosity values, it turned out to be not suitable for refractive index matching with acrylic models (1.485 compared to 1.491) without adding high optical density liquids. The other anise oil sample has a higher refractive index 1.495 while the dynamic viscosity is also twenty times higher than the transparent anise oil. One of the main disadvantages of anise essential oil that was not mentioned in [1] is its toxicity according to the GHS classification: H341 - Suspected of causing genetic defects, and H351 - Suspected of causing cancer. This property makes it questionable using aniseed oil in hydrodynamic experiments can be done on a large scale, because while the specific odor can be reduced by using tight seals and isolation possible spills and direct skin exposure might be potentially harmful to health of the personnel.

Table 1. Physical properties of immersion solutions at 23°C.

Type	Refractive index	Dynamic viscosity (cP)	Comment
NaI, 50%	1.435	1.52±0.05	Unstable at daylight
p-Cymene	1.493	0.876±0.03	H226 Flammable liquid and vapour
Anise oil (transparent)	1.482	1.02±0.01	GHS toxicity H341, H351
Anise oil (yellow)	1.495	21.07±0.14	GHS toxicity H341, H351, Increased viscosity
White mineral oil	1.469	24.05±0.13	Increased viscosity

Table 2. Physical properties transparent rod models at 23°C.

Type	Refractive index	Comment
Acryl	1.491	Low melting temperature
Quartz	1.468	High melting temp., fragile
Glass	1.52	High refractive index, fragile

The last liquid tested in Table 1 of white mineral oil composed of saturated hydrocarbons having a predominant number of carbons in the range of C15 to C50 has a refractive index of 1.469, which is lower than for acrylic models. However, it can match fairly well the quartz glass samples, while it is almost odorless and has less impact on health when inhaling or skin exposure. Some modifications of white mineral oil (liquid paraffin) have grades for food equipment lubrication or have even been used for medical purposes peroral and cosmetics production. The main difficulty with using mineral oil similar to that of yellow anise oil is the higher values of dynamic viscosity compared to those of water. This imposes additional restrictions on a pump hydraulic head in order to promote enough mass flow rate to achieve turbulent conditions in a model fuel rod assembly channel. One solution may be to heat the working fluid above ambient temperature; however, this can lead to adversarial temperature gradients with a change in the refractive index inside the working area distorting the field of view in optical measurements.

Measured temperature dependence of the refractive index for two immersion fluids of yellow anise oil and white mineral oil in the range 20-30°C. The data obtained are shown in Figure 2. The graph shows a weak dependence of RI in the specified temperature range with ΔRI=±0.002 and ±0.0025 for mineral oil and aniseed oil correspondingly. According to the paper [3] temperature drift of RI for solids is several times less than for liquids. Within this working temperature range it is not necessary to stabilise the working fluid.

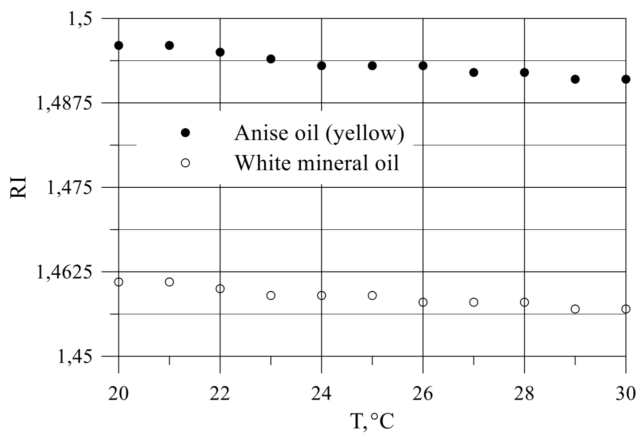

Fig. 2. Temperature dependence of RI for aniseed oil and white mineral oil.

4 Conclusion

We tested different options of refractive liquid and transparent solids pairs for doing optical measurements using the MIR technique to decrease optical distortions in curved wall channels. White mineral oil was selected together with quartz cylindrical tubes for our further experiments to study the heat and mass transfer in models of rods in fuel assemblies of nuclear reactors. This was done due to the acceptable match of RI for both substances, as well as due to the low toxicity of white mineral oil compared to other substances considered in the work.

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