Metamaterial for Simulation of Imaging Through Nanodroplets in Wet Steam

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Abstract: We describe a metamaterial that simulates scattering by steam nanodroplets. Fabricated samples made with alumina nanoparticles compare favorably to previous powerplant measurements. Imaging at 850 nm demonstrates potential for in situ inspections through steam.

1. Introduction

Automated inspection with machine vision is being deployed broadly in various industrial applications for defect detection. The ability to do in situ imaging of an operating powerplant could reduce the need for extensive equipment shutdown during periodic inspections, which is current practice. However, the wet steam environment in the low-pressure section of powerplant steam turbines creates unique imaging challenges because a highly scattering atmosphere surrounds large rotating turbine blades, which often move faster than the speed of sound. This atmosphere consists of steam vapor in vacuum with a dense cloud of water nanodroplets [1,2] that obscures the blades and is difficult to replicate in a laboratory. The 100 to 300 nm nanodroplets are 10-100 times smaller than water droplets in fog [3], resulting in a strong wavelength dependence not encountered with fog [4].

2. Design, Fabrication and Test Results

For imaging studies and system development, a steam-like metamaterial was designed to closely match the wavelength dependence of scattering by water nanodroplets. Several different combinations of nanoparticles and host materials were considered based on refractive index (n), modeling results, off-the-shelf availability, and ease of use. Figs. 1a and 1b, calculated using MiePlot for Mie scattering by a sphere, compare water steam extinction with a steam-like metamaterial based on nanoparticles with 1.75 refractive index embedded in a host material with 1.47 index. Fig. 1c is a comparison for the final selected design showing an excellent match between wet steam and simulated steam, with curves normalized at 400 nm because nanoparticle density can be adjusted during fabrication. It is interesting to note that the ratio of refractive indices is not the same for the two cases.

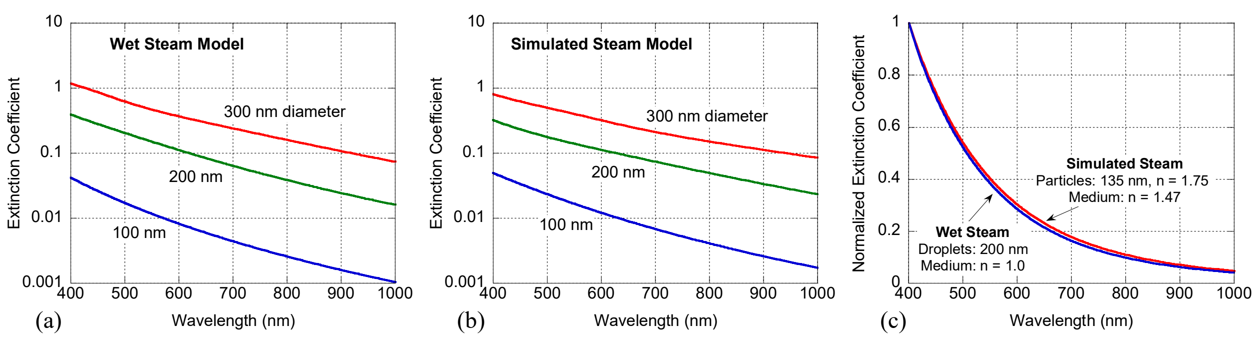

Fig. 1. Model of wavelength dependence for (a) wet steam, (b) simulated steam, and (c) wet steam versus simulated after normalization.

Steam-like samples with various particle densities were fabricated by dispersing 135 nm alumina nanoparticles (US Research Nanomaterials US3003) in a transparent candle gel designed for suspension of ingredients (Penreco Versagel CHP). These materials have refractive indices close to the indices used in the simulated steam model. A homogeneous and relatively dense mother sample was created in a beaker on a hot plate, using a magnetic stirrer to mix nanoparticles with candle gel. This mother sample was then used to create multiple diluted samples directly in large glass cuvettes (50 x 50 x 50 mm internal dimensions), employing only thermally-induced mixing. The fabricated samples have a very uniform steam-like appearance, with the densest appearing white in reflection and orange in transmission. Refraction by the samples is expected to produce minimal aberrations after focus adjustment because most imaging systems of interest have an object space numerical aperture (NA) less than 0.1.

Fig. 2a is a photograph of a sample illuminated with red, green and blue laser beams that illustrates increased scattering at shorter wavelengths. (The curved red line is a reflection.) Transmission was measured at various laser wavelengths between 400 and 900 nm for comparison with previous measurements from a powerplant steam turbine [2]. Measurements at 405 and 450 nm were performed using individual semiconductor lasers, while those at longer wavelengths were made using a supercontinuum laser with an acousto-optic tunable filter. Fig. 2b shows the results for 4 samples with different densities of alumina nanoparticles between 0.024% and 0.165% by weight. Contributions from reflections and slight loss in the candle gel itself were removed by dividing measured results by those for a gel sample without any added nanoparticles. Fig. 2c compares sample B results with those in the low-pressure section of a powerplant steam turbine at various radial positions along the discharge of the steam turbine blade, after adjusting to match the 25 mm optical path length of the turbine probe. The transmission of this sample, which has lowest nanoparticle density, is very similar to powerplant measurements at least transmissive locations.

To evaluate imaging through the simulated steam, test targets were imaged with a monochrome industrial camera with a 0.07 NA lens and illumination from LED arrays. Fig. 3 shows results for two different samples with 455 and 850 nm illumination. As expected, images at 850 nm are much clearer than those at 455 nm with Fig. 3b showing excellent visibility of the test target for scattering similar to that caused by 50 mm of powerplant steam.

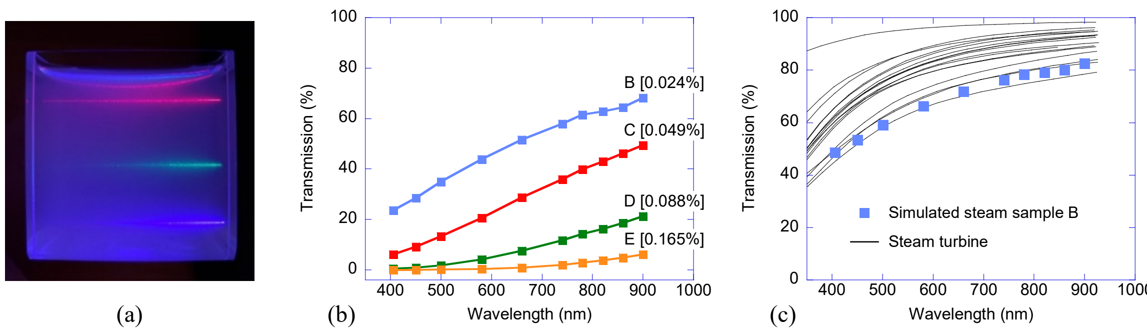

Fig. 2. (a) RGB laser beams in sample, (b) transmission for 50 mm path with different nanoparticle densities as noted on curves, and (c) sample B transmission for 25 mm path versus steam turbine measurements at different radial positions.

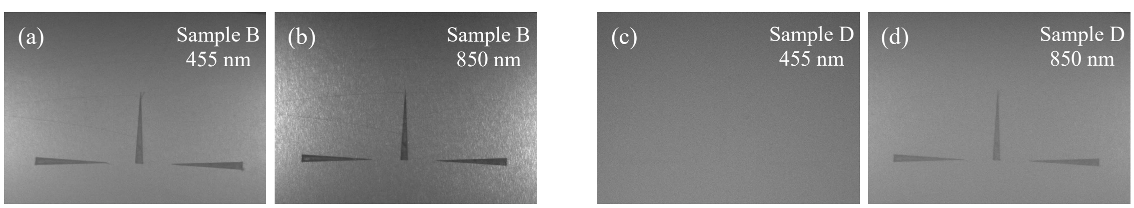

Fig. 3. Images of test targets with 0.5 x 5.0 mm triangles through simulated steam samples B and D at 455 nm and 850 nm.

3. Conclusion

We have designed, fabricated and tested a semisolid metamaterial with light scattering properties that closely match those of nanodroplets found in powerplant condensing steam turbines. Imaging through the steam-like samples in the near infrared, where high power LEDs are readily available and CMOS image sensors have good sensitivity, shows promise for in situ power plant inspections through steam during operation. A report on a prototype imaging probe for this purpose has been published by Electric Power Research Institute (EPRI), Inc. [5].

The results described here are used with permission from EPRI, who provided funding for this work.

4. References

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