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Enhancement of solar radiation absorption using nanoparticle suspension

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Abstract

The radiation absorption characteristics of a Ni nanoparticle suspension were investigated by spectroscopic transmission measurement. It was demonstrated that the absorption coefficient of the nanoparticle suspension is much higher than that of the base liquid for visible to near-infrared wavelengths. Radiation characteristics predicted by the Mie theory showed good agreement with the increase of absorption coefficient in wavelengths where the base liquid is transparent. It was also confirmed that a new transmittance measurement technique for a liquid sample using a liquid cell with no spacer was quite useful for evaluating a material possessing an extremely strong absorption band. The proposed measurement method and successive Kramers–Kronig analysis were validated by measuring the optical properties of water. The measurement and prediction process of the thermal radiation properties of nanoparticle suspensions developed here could be used in developing direct absorption solar collectors.

Keywords: Nanoparticle suspension; Optical properties; Absorption enhancement; Spectral transmittance measurement; Non-spacer technique; Solar thermal energy

1. Introduction

Solar thermal collectors are energy conversion devices that absorb the radiant energy of solar irradiation and transfer it as thermal energy to a fluid. Diverse types of solar collectors are available for a very wide range of applications (Kalogirou, 2004). Many collectors absorb the incident radiation at black or spectrally selective surfaces. In addition, a different concept of volumetric absorption has been proposed and investigated through some approaches, including the use of a porous medium (Grald and Kuehn, 1989) and particles suspended in a fluid (Minardi and Chuang, 1975; Drothing, 1978; Bertocchi et al., 2004). Recently, a direct absorption solar collector using a heat transfer fluid into which aluminum nanoparticles were suspended was proposed and its performance was numerically evaluated (Tyagi et al., 2009).

In designing a direct absorption solar thermal system utilizing a liquid suspending small particles, the thermal radiation characteristics of the suspension and the optical properties of the base fluid are indispensable (Kumar and Tien, 1990). The absorption coefficient is used when determining the ability of the suspension to absorb solar irradiation and also when estimating the energy loss due to the emission of thermal radiation. The refractive index of the base fluid, or the effective refractive index for high particle volume fraction (Kreibig and Vollmer, 1995), is used to calculate the reflective and refractive properties at the interface between the fluid and other materials such as transparent cover plates. It is also used in the prediction of particle radiation properties that are estimated from the Mie theory as a function of the particle size parameter

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and the refractive index relative to that of the surrounding medium (Bohren and Huffman, 1998).

A spectroscopic transmission measurement using a liquid cell may be used to acquire the optical properties of liquids over a wide range of wavelengths. However, the difficulty of the measurement lies in the quantitative evaluation of the complex refractive index. Although simultaneous determination of the real and imaginary parts of the complex refractive index by analyzing transmittance while considering the optical behavior inside a liquid cell is possible in theory and has been applied to infrared cases (Tuntomo et al., 1992), maintaining accuracy in the transmittance analysis including coherent behavior is an experimentally complicated matter. Even for measurements conducted under the incoherent condition, the real part of the complex refractive index is exceedingly sensitive to any experimental error and failure to acquire it has been reported (Otanicar et al., 2009). Furthermore, when the sample liquid has a strong absorption band, a specially developed liquid cell such as a wedge-shaped cell has been required in order to detect transmission through an extremely thin sample layer, which greatly complicates the experimental setup and procedure (Wieliczka et al., 1989).

A transmission measurement for successive, but not simultaneous, determination of the real and imaginary parts of the complex refractive index requires a wide spectral range for the imaginary part, because the method is based on the use of the Kramers–Kronig analysis that provides dispersion of the real part from the spectrum of the imaginary part. Acquisition of the imaginary part is particularly important in case of an extremely strong absorption band, because it greatly affects the subsequent processes for obtaining the real part. Although such a measurement in the infrared region for liquid hydrocarbon fuels exhibiting a strong absorption band due to C–H stretching vibration has been reported (Porter et al., 2009), developing a transmission measurement procedure applicable to a much wider wavelength range and strength of absorption bands is desirable.

Thermal radiation characteristics of liquids, especially their absorption property, are expected to increase greatly for visible wavelengths when particles that absorb radiation of these wavelengths are dispersed. Optical properties of nanoparticles, which depend on their material, shape and size, have been reported in numerous studies, and their optical properties can be numerically predicted through electromagnetic wave analysis (Kreibig and Vollmer, 1995). The remarkable utilization of nanoparticles designed as a spectrally selective radiation absorber has been proposed (Hirsch et al., 2003). Application of nanoparticles in a solar direct absorber provides a new approach to the development of solar collectors.

In this study, spectroscopic transmission measurements of the radiation absorption characteristics of a Ni nanoparticle suspension were conducted. A new measurement technique was developed to acquire the absorption property at an extremely strong absorption band. The proposed procedure was validated by measuring the optical constants of water. Furthermore, the effect of the dispersion of nanoparticles into a liquid on the thermal radiation characteristics was investigated through numerical analysis based on the Mie theory.

2. Measurement setup

2.1. Spectroscopic measurement

Transmission measurements were made using a Fourier transform infrared (FT-IR) spectrometer (JASCO, 6100) and a UV/VIS/NIR spectrophotometer (JASCO, V-670). A deuterated l-alanine triglycine sulfate (DLATGS) pyroelectric detector was used in the FT-IR spectrometer. In the UV/VIS/NIR spectrophotometer, a PbS photodiode was used for the near infrared measurement and a photomultiplier was used in the visible range. None of the detectors used needed a cooling device. All measurements were made at a pressure of 1 atm and room temperature. These two spectrometers support successive transmission measurements because an identical liquid cell into which liquid samples are injected can be mounted in the sample compartments of both spectrometers.

A variable-path-length liquid cell (JASCO, K-type) was used in the transmission measurement, and its configuration is shown schematically in Fig. 1. It is assembled from transparent windows, rubber sheets, and a spacer that determines the sample thickness, and these components are tightened by front and back plates with four nuts and bolts located at the four corners of the plates. The aperture diameter of the liquid cell is 25 mm. The window material was 3-mm-thick CaF_2 chosen for its transparency in the infrared range. The path length of a sample could be varied by selecting spacers of different thicknesses: Pb amalgam sheets of thicknesses ranging from 0.025 to 0.2 mm and 0.006-mm-thick polyethylene film. The thickness of a spacer was determined based on the detected intensity of

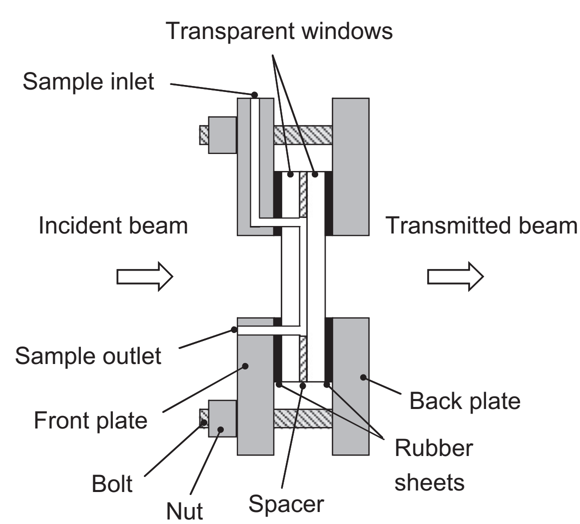

Fig. 1. Cross sectional view of the liquid cell used for transmission measurements. A spacer is removed when measuring transmittance at extremely strong absorption bands.