

Infrared Reflection Removal in Wind Tunnels using Polarization Theory

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Infrared radiometry with infrared cameras allows for high spatial resolution, noncontact measurements in wind tunnel experiments and has been increasingly used to visualize flow features. Reflections from test section walls present a major challenge in collecting these measurements as it is difficult or impossible to separate them from the true model emission signal. This paper implements a method to quantitatively separate the reflections from the emission using polarization theory. Samples with a range of emissivities were tested, and in all samples the reflections were significantly reduced. This method will lead to more accurate radiometric and thermographic measurements in wind tunnel experiments.

Nomenclature

n	=	index of refraction
ε	=	emissivity
ρ	=	reflectivity
ρ_s	=	s-polarized reflectivity
ρ_p	=	p-polarized reflectivity
τ	=	transmissivity
E	=	energy
E_e	=	emitted energy
E_r	=	reflected energy
E_s	=	s-polarized energy
E_p	=	p-polarized energy
θ	=	angle of incidence
I	=	pixel intensity
u	=	uncertainty

I. Introduction

Infrared (IR) radiometry is a nondestructive, noncontact measurement technique that measures thermal radiation emanating from a surface and has been increasingly used in production-level wind tunnels for flow field temperature visualizations. Research-grade mid-wave IR cameras are typically utilized for IR radiometry in wind tunnels due to their high spatial resolution and high sensitivity. IR radiometry images of a model surface are useful to identify aerodynamic features such as boundary layer transitions and shock impingements [1–3].

Without significant and unrealistic prior knowledge, a single image cannot be used to differentiate an IR camera signal due to model emission from that of background reflection. In a wind tunnel test environment, the test-section

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walls act as a radiative source of infrared light which is reflected by the model surface into the camera [4]. For aluminum or steel models with high reflectivity, the background reflections will dominate the signal in the images [5].

One solution is to paint the model surface with a flat black paint to reduce the reflectivity and increase the emissivity [4,6]. This also serves to increase the temperature gradients on the model surface by decreasing the thermal conductivity. The flat black paint reduces the reflectivity of the metal surface from roughly 90% to 12% [4].

Unfortunately, not all production-level tests are able to paint the model surface in this manner. Some tests may require or desire the surface finish of the bare metal to preserve certain boundary layer effects. Additionally, other simultaneous measurement techniques may also require a surface coating such as fast-response Pressure-Sensitive Paint (PSP) [7] or random ink speckles for model deformation measurements [8].

This paper presents a method to use polarization theory to quantitatively separate emission from background reflection. This method requires two images, one captured with a polarizer at 0° and one at 90° . The only material property needed is the index of refraction.

II. Theory

A. General Theory

All energy that reaches an object is absorbed, reflected, or transmitted. All energy emanating from an object is from emission, reflection, or transmission. The assumptions will be made that the model is opaque in the infrared spectrum and at steady state or at least quasi-steady state. With those assumptions we can ignore the absorption and transmission terms which implies emissivity (ε) and reflectivity (ρ) sum to unity, as given in Eq. (1).

$$1 = \varepsilon + \rho \quad (1)$$

According to the Fresnel formulas and Snell's law, reflectivity and emissivity are functions of the angle of incidence (AOI, θ) which is purely geometric, and the index of refraction (n) of the material which is assumed to be constant [9,10]. AOI refers to the angle between the surface normal vector and the vector from the surface to the camera sensor at the point of interest. The materials are assumed to be dielectric, and so n is used to denote real values for index of refraction. The method is still valid for materials that are not dielectrics (i.e., conductive materials), but then the index of refraction will have an imaginary term for coefficient of extinction and would be more properly denoted with the variable Z .

Reflectivity for p- and s-polarizations (ρ_p and ρ_s , respectfully) as a function of AOI and index of refraction are given Eqs. **Error! Reference source not found.** and **Error! Reference source not found.**. Equations (1), (2), and (3) were experimentally confirmed in [11]. Figure 1**Error! Reference source not found.** shows a representative plot of reflectivity for the p- and s- polarizations.

$$\rho_p(\theta) = \left(\frac{n^2 \cos \theta - \sqrt{n^2 - \sin^2 \theta}}{n^2 \cos \theta + \sqrt{n^2 - \sin^2 \theta}} \right)^2 \quad (2)$$

$$\rho_s(\theta) = \left(\frac{\cos \theta - \sqrt{n^2 - \sin^2 \theta}}{\cos \theta + \sqrt{n^2 - \sin^2 \theta}} \right)^2 \quad (3)$$

$$E = \varepsilon \tau E_e + \rho \tau E_r \quad (4)$$

$$E = (1 - \rho) \tau E_e + \rho \tau E_r \quad (5)$$

$$E_p = (1 - \rho_p) \tau \left(\frac{E_e}{2} \right) + \rho_p \tau \left(\frac{E_r}{2} \right) \quad (6)$$

$$E_s = (1 - \rho_s) \tau \left(\frac{E_e}{2} \right) + \rho_s \tau \left(\frac{E_r}{2} \right) \quad (7)$$

The energy into the camera can be defined as the sum of the emission and reflection that reach the camera. This is defined rigorously in Eq. (4) where E is the radiation that reaches the camera, E_e is the black body radiation emanating from the model, E_r is the reflection radiation, and τ is the transmissivity of the mediums between the camera and model. Equation (5) simply replaces ε with $1 - \rho$ from Eq. (1).

Malus' law states that emitted and reflected energy are each reduced by half through a polarizer [12]. From this fact Eq. (6) can be derived for the energy observed by camera with a p-polarizer (E_p) and Eq. (7) for an s-polarizer (E_s). By solving the simultaneous Eqs. (6) and (7), the emitted energy can be quantitatively separated from the reflected energy [11] or vice versa. Additionally, the average of E_p and E_s yields E , the total energy to the camera.

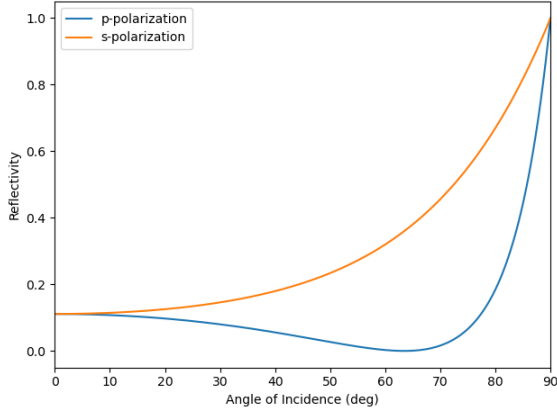


Fig. 2: Reflectivity for p- and s- Polarization of Index of Refraction of 2.0

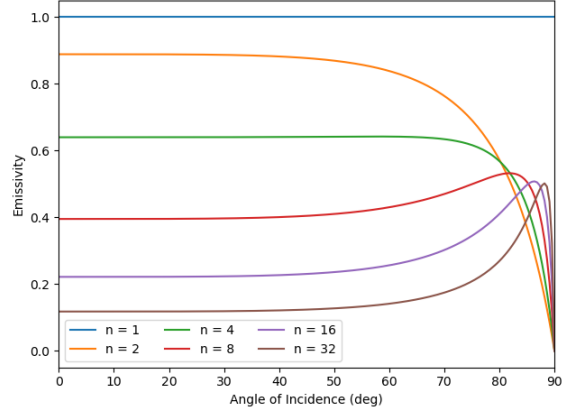


Fig. 2: Emissivity vs AOI for various Indices of Refraction

B. Limitations

For small angles of incidences, reflectivity in the p- and s-polarizations are very close in magnitude. The cutoff for ‘small angle’ is a function of the reflectivity, but for reasonable reflectivity values the cutoff will be below 20°. Almost all the uncertainty terms for the model emission feature ($\rho_p - \rho_s$) in the denominator, so for small AOI those terms are very large. Further explanation of uncertainty is given in the Section V, Uncertainty Quantification.

In order for the AOI to be small, the reflection source must be relatively close to the camera. In a large tunnel such as the Unitary Plan Wind Tunnel (UPWT) at NASA Ames Research Center, the model is nominally 5.5 feet from the camera. Even at that large distance, a 20° AOI would correspond to a source approximately 2 feet from the camera. While that is a significant limitation for the method, some care can be taken to avoid positioning the camera near strong sources of IR radiation such as motors or heat pumps. Additionally, if the uncertainty of the method is too large for small angles and degrades the overall performance, the sum of the p- and s-polarized images can be averaged to find the unpolarized image. The unpolarized image will contain the both the emission and reflection as if the method did not exist.

Equations (1), (2), and (3) can be combined to derive the unpolarized emissivity as given in Eq. (8). Figure 2 shows emissivity for various indices of refraction across 0° to 90° of AOI. For large AOI (roughly 70°), the emissivity becomes very sensitive to changes in AOI. At that point small errors in estimating the AOI will result in large errors in emissivity and reflectivity ultimately leading to high uncertainty in the model emission. This not currently a concern in a wind tunnel setting since optical measurement techniques already avoid AOI greater than 70° as too much of the model surface area will be imaged by too few pixels [7].

A final limitation is the fact that since polarizers reduce the incoming signal by half, all else equal, the images will have half the intensity. This will decrease the signal to noise ratio (SNR) of the system since read noise is constant and shot noise is the square root of the intensity. However, this issue can be sidestepped by doubling the exposure time of the camera. While not ideal, a high frame rate is not typically required since the thermal gradients do not change very quickly in time.

$$\varepsilon = 1 - \left\{ \left(\frac{n^2 \cos \theta - \sqrt{n^2 - \sin^2 \theta}}{n^2 \cos \theta + \sqrt{n^2 - \sin^2 \theta}} \right)^2 + \left(\frac{\cos \theta - \sqrt{n^2 - \sin^2 \theta}}{\cos \theta + \sqrt{n^2 - \sin^2 \theta}} \right)^2 \right\} \quad (8)$$

III. Experiment

A. Samples to be Tested

To test the feasibility of the method, three samples will be used: a bare aluminum sample, an aluminum sample painted with flat black polyurethane paint, and an aluminum sample painted with fast-response PSP [13]. The aluminum sample represents the worst-case where painting the model is not feasible. The aluminum sample not only has low emissivity, estimated to be 10% based on previous experiments, but is also not a dielectric and so the index of refraction will have an imaginary term for the extinction coefficient. The sample painted with black polyurethane paint represents the best-case as it has high emissivity, estimated to be 88% based on previous experiments, and will act as a dielectric. The polyurethane paint is commonly employed at the UPWT for similar IR measurements due to

its excellent material properties [4,6]. The sample painted with PSP represents an intermediate case where both pressure and thermal radiation maps are desired. PSP also acts as a dielectric and has an emissivity between the bare aluminum and black paint.

The reflection removal method requires the characterization of the index of refraction. Emissivity is a function of index of refraction as given in Eq. (8), and Eq. (9) gives the emissivity at zero AOI [10,11]. The emissivity can be measured using the method outlined in Appendix A of [4], which also has the benefit of correcting for the system response curve of the IR camera. However, that method has high uncertainty for samples with high emissivity. Other methods for determining the emissivity and index of refraction would include locating Brewster's angle [11], which has high uncertainty for low emissivity, or ideally an infrared spectrometer.

$$n = \frac{2 - \varepsilon + 2\sqrt{1 - \varepsilon}}{\varepsilon} \quad (9)$$

B. Experimental Setup

The experiment will be broken into two segments: a one-camera setup, and a two-camera setup. Both setups will feature the FLIR SC6100 (3-5 μm) IR camera(s) with all three samples in view simultaneously. A hotplate will be used to act as the reflection source. The cameras are expected to operate with gain setting 2 at 20 frames per second. For both setups, temperature on the surface of the hotplate and samples will be measured with thermocouples. Additionally, images with and without the reflection source will be gathered for comparison to the method's output. Between any changes to the setup, ample time will be given for the system to reach steady state. A similar setup from a previous experiment is shown in Fig. 3.

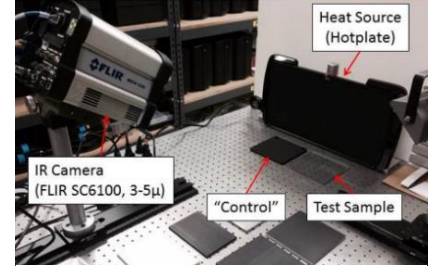


Fig. 3: Similar Experimental Setup

For both setups, internal and external calibration [14] will be performed on the camera(s). Each sample will have small markers with known positions in order to perform the external calibration. A 3D mesh will be made of the sample coupon geometry, and the AOI will be determined for every mesh node based on the external calibration. The mesh will be constructed such that for the one-camera setup, each pixel corresponded to almost exactly 1 mesh node. This process can be directly applied to more complex geometry, such as a wind tunnel model.

The one-camera setup is intended to verify the feasibility of the method with the materials that are common in UPWT tests and identify adverse effects that are related to pixel position such as vignetting or narcissism [2]. For this setup, only one camera will be used, and the polarizers are used in series to capture the p- and s-polarization images. This method works in the lab as everything is stationary and at steady state. The one-camera setup also has the benefit that the two images can be directly compared since they are captured from a single location.

The two-camera setup is intended to test a way to apply the method to a production-level test. The two-camera setup will utilize one camera with an s-polarizer, and one with a p-polarizer. The images can be acquired simultaneously but will not be taken from the exact same position. Two-cameras are required outside the lab since the model may only be at quasi-steady state and so the images cannot be separated in time. Additionally, outside the lab it is impractical to swap the polarizer for every data collection sequence as is done for the one-camera setup. The two-camera setup sidesteps these issues, but it brings its own set of new issues. For one, it increases the complexity, cost, power, and size of the setup. Additionally, since the image are no longer taken from the same location, the measurements will need to be projected to a 3D model mesh to find correspondences between cameras. A method similar to that employed in [7] and [15] will be used for projection. Furthermore, the AOI now varies for the polarized images which means the θ of Eqs. (2) and (3) are no longer the same and will need to be calculated independently.

IV. Expected Results

A. Index of Refraction

The emission and index of refraction will be determined for the painted samples assuming the samples act as a dielectric. The index of refraction for the bare aluminum sample will not be assumed to act a dielectric and thus will have an imaginary term for the coefficient of extinction. To determine the index, a method similar to that of Appendix A in [4] will be used over an entire image of a given sample. The optimal indices of refraction, and coefficient of extinction for the bare aluminum sample, will be found with a least-squares solver by minimizing the error between the observed and theoretical signal over the entire sample surface.

Based on previous experiments, the indices of refraction are estimated to be 2.06, 7.87, and $6.21 + 12.38i$ for the black paint, PSP, and bare aluminum, respectively. A plot of the emissivity as a function of AOI based on these

estimates is shown for each sample in Fig. 4. The plot clearly shows the ranking of emissivities, as well as the large gradient that occurs for all samples above 70°.

B. Camera Calibration

The internal calibration will be performed with a custom 14x12 checkerboard calibration board from Calib.io [16] made with a Lambertian substrate. The Calib.io Camera Calibration software will be used to perform the internal calibration as well. The external calibration will be performed using custom software to locate the circular markers on the samples and used OpenCV's Perspective-n-Point algorithm with RANSAC to determine the optimal relative rotation and translation from the camera to the sample.

C. One-Camera Setup

The one-camera setup will allow for direct comparison between images. For visualization, three images will be provided: an image taken with no polarizer and no reflection, an image with no polarizer and reflection, and the image of the emission constructed from the polarized images (with the artificially reflection removed).

Qualitatively, the constructed image of the emission should be visually similar to the actual image with no reflection. The black painted sample should be particularly convincing. The bare aluminum sample may have several visual artifacts that give away its artificial nature due to its high reflectivity. The PSP painted sample will be somewhere between the black paint and bare aluminum due to the relative rankings of the emissivities.

The image with no reflection will be compared to the constructed emission image for a more quantitative measure, but there may be issues with that metric as the system will vary slightly over time.

D. Two-Camera Setup

The two-camera setup is a more representative case of performance in the wind tunnel. For visualization, a similar set of 3 images will be provided: an image from camera 1 with no polarizer and no reflection, an image from camera 1 with no polarizer and with reflection, and an artificial image of the emission constructed from the polarized images (with the artificially reflection removed). The constructed emission image is synthetic but will be generated from the view of camera 1 for a more direct comparison with the non-polarized images.

Qualitatively, the constructed image should again be convincing. Visually the reflection should be again almost completely removed for the black painted sample. The bare aluminum is expected to show similar artifacts to the one-camera case. The PSP sample will again be somewhere between the other two samples.

A similar qualitative comparison between the constructed and reflectionless image will be performed.

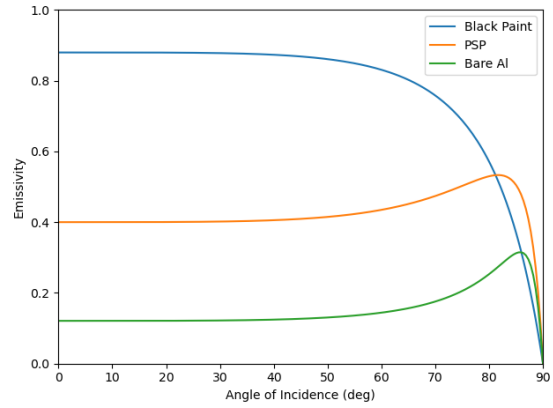


Fig. 4: Emissivity vs AOI for Tested Samples

V. Uncertainty Quantification

From Eqs. (6) and (7), the emission energy can be solved for directly as given in Eq. (10). The emission energy is a function of the images, index of refraction, angle of incidence, and transmission efficiency. All inputs are uncorrelated, and the resulting uncertainty is defined in Eq. (11). A visualization of the uncertainty will be given per-pixel/node for the one/two-camera setups.

$$E_e = \frac{2E_s\rho_p - 2E_p\rho_s}{\tau(\rho_p - \rho_s)} \quad (10)$$

$$(u(E_e))^2 = \left(\frac{\partial f_{E_e}}{\partial I_{E_s}} u(I_{E_s}) \right)^2 + \left(\frac{\partial f_{E_e}}{\partial I_{E_p}} u(I_{E_p}) \right)^2 + \left(\frac{\partial f_{E_e}}{\partial n} u(n) \right)^2 + \left(\frac{\partial f_{E_e}}{\partial \theta} u(\theta) \right)^2 + \left(\frac{\partial f_{E_e}}{\partial \tau} u(\tau) \right)^2 \quad (11)$$

The first terms are related to the image noise, of which the main component is shot noise. Dark current is ignored since the exposure time is relatively small, quantization noise and read noise are ignored since their contribution is small. Fixed pattern noise effects such as lens vignetting, or narcissism would be included in this term as well but are ignored for this analysis. A future experiment should aim to perform a flat field correction to correct for those fixed pattern sources of noise. The image noise, as well as image sensitivities, are defined in Eqs. (12), (13), and (14).

$$u(I) = \sqrt{u_{shot}^2} = \sqrt{I} \quad (12)$$

$$\frac{\partial f_{E_e}}{\partial I_{E_s}} = \frac{2\rho_p}{\tau(\rho_p - \rho_s)} \quad (13)$$

$$\frac{\partial f_{E_e}}{\partial I_{E_p}} = \frac{-2\rho_s}{\tau(\rho_p - \rho_s)} \quad (14)$$

The next term is the uncertainty related to the index of refraction. A similar method to that used in Appendix A of [4] will be used to measure the index of refraction, and the index of refraction uncertainty will be related to that method. The index of refraction sensitivity is given in Eq. (15). The reflectivity sensitivities with respect to the index of refraction are omitted due to their length and complexity when accounting for a complex index.

$$\frac{\partial f_{E_e}}{\partial n} = \frac{2(E_s - E_p) \left(\rho_p \frac{\partial \rho_s}{\partial n} - \rho_s \frac{\partial \rho_p}{\partial n} \right)}{\tau(\rho_p - \rho_s)^2} \quad (15)$$

The next term is the uncertainty related to AOI. The uncertainty in AOI is the combination of the uncertainty in camera calibration plus the angle estimation due to the pixel discretization. Using Monte Carlo uncertainty estimation, the camera calibration uncertainty was found to be within 1 pixel 99.74% of the time. Accounting for the fact that a single position is used for an entire pixel, the maximum pixel error in AOI estimation is 1.71 pixels. The maximum AOI uncertainty can then be determined assuming the true 3D position of a node is within 1.71 pixels of the localized position. The AOI sensitivity is given in Eq. (16). The reflectivity sensitivities with respect to the index of refraction are omitted due to their length and complexity when accounting for a complex index.

$$\frac{\partial f_{E_e}}{\partial \theta} = \frac{2(E_s - E_p) \left(\rho_p \frac{\partial \rho_s}{\partial \theta} - \rho_s \frac{\partial \rho_p}{\partial \theta} \right)}{\tau(\rho_p - \rho_s)^2} \quad (16)$$

$$u(\theta) = f(1.5)_{pixel\ localization} \quad (17)$$

The final term is the uncertainty related to transmissivity. The transmissivity through air is assumed to be 100% efficient since the distances in our experiment and in wind tunnels will be too small to have an effect. The transmissivity of the polarizer is a manufacturer specification or can be measured experimentally with a light meter. The transmissivity sensitivity is given in Eq. (18).

$$\frac{\partial f_{E_e}}{\partial \tau} = -\frac{(\rho_p - \rho_s)(2E_s\rho_p - 2E_p\rho_s)}{\tau^2} \quad (18)$$

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