2004

NASA FACULTY FELLOWSHIP PROGRAM
Accompanying Student

MARSHALL SPACE FLIGHT CENTER

THE UNIVERSITY OF ALABAMA
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE
ALABAMA A&M UNIVERSITY

Optical Cryogenic Tank Level Sensor

Prepared By:	Amanda Duffell
Academic Rank:	Graduate Student
Institution and Department:	University of Alabama in Huntsville, Department of Physics
Professor Accompanied:	Prof. Don A. Gregory
NASA/MSFC Directorate:	Transportation
MSFC Colleague:	John Wiley

Introduction

Cryogenic fluids play an important role in space transportation. Liquid oxygen and hydrogen are vital fuel components for liquid rocket engines. It is also difficult to accurately measure the liquid level in the cryogenic tanks containing the liquids. The current methods use thermocouple rakes, floats, or sonic meters to measure tank level. Thermocouples have problems examining the boundary between the boiling liquid and the gas inside the tanks. They are also slow to respond to temperature changes. Sonic meters need to be mounted inside the tank, but still above the liquid level. This causes problems for full tanks, or tanks that are being rotated to lie on their side.

The Transportation Directorate is currently working on an optical probe to measure tank level. It would offer a fast, cheap and reliable alternative to the present measuring methods. Two designs are being developed. One is based on evanescent light wave coupling from a solid quartz rod or optical fiber to the surrounding liquid. The second is based on losses in a series of engineered air/glass interfaces in a segmented quartz rod or notched optical fiber.

Theory

The propagation of light through a waveguide is controlled by the refractive indices of the guide and its surrounding medium. Snell's Law is the basic equation to explain refraction phenomenon, Eqn. 1, Fig. 1.

Equation 1 $$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

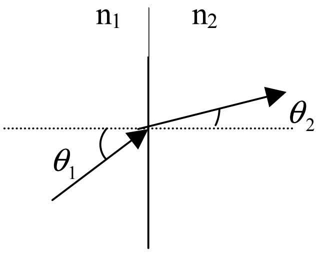


Figure 1 Illustration of Snell's Law with n2 > n1

Total Internal Reflection (TIR) is the effect of light reflecting predominantly inside the medium of high refractive index, instead of refracting and passing through a boundary to a medium with lower refractive index. TIR occurs when $\theta_2 \geq \theta_c$. The critical angle, θ_c, is when $\theta_1 = 90°$. At that point, all light at the n_2:n_1 boundary reflects back into material n_2.[1] TIR is critical to transmitting light through a waveguide, such as an optical fiber or a piece of quartz tubing, Fig 2.

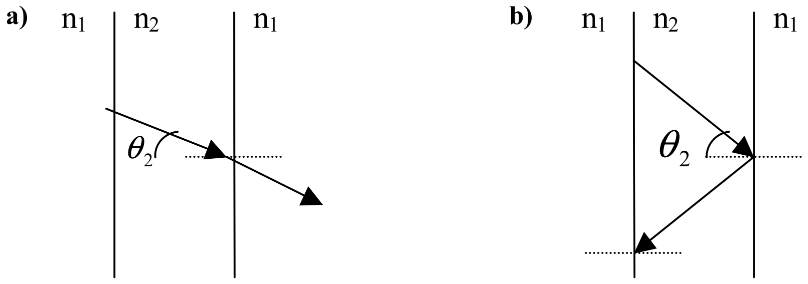


Figure 2 Case a) $\theta_2 \le \theta_c$, no TIR occurs Case b) $\theta_2 \ge \theta_c$, TIR occurs

TIR is most efficient when $n_2 - n_1$ is large because a greater range of angles can propagate through the medium n_2. For example, light will propagate with less loss through glass surrounded by air than water, Table 1.

Material	Index of Refraction
Glass	1.46
Water	1.3
Air	1
Plastic Fiber	1.33

Table 1 Indices of Refraction

Evanescent coupling occurs when light propagates through surface modes on a material. The surface modes allow transfer of light from the propagation medium to its surrounding. Evanescent coupling is most efficient when the two materials have similar refractive indices.[2]

The main source of loss in an optical system is material interfaces. These losses can be estimated by the Fresnel reflectance, R, and transmittance, T, Eqn. 2 and 3, for normal incidence.

Equation 2 $$r = \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2$$

Equation 3 $$t = 1 - r$$

From these equations, it can be seen that transmission losses from one material to another can be minimized when the refractive indices are more similar.[3]

Experimental

Two different methods were used in designing the optical tank level probes. One depends on evanescent coupling effects and the other is based on Fresnel reflection losses.

Evanescent Coupling

The evanescent coupling probes used optical fiber for the waveguide and air, water, or liquid nitrogen as the coupling medium. The basic concept for this design is that the fiber would transmit more effectively in air than in liquid because of the refractive index difference. Because evanescent modes couple through the surface of the fiber, it was important to remove the fibers' cladding, or to choose fibers that were not clad.
When the cladding is removed from glass fibers they become very brittle and difficult to work with, especially in large lengths. Large path lengths are necessary because evanescent coupling is a weak effect and needs to occur over a long section of fiber for the effects to be measurable. The handling problems made glass fibers a poor probe choice.

An alternative to glass fiber is plastic fiber. The plastic fiber is pliable and not brittle, so it does not require cladding to be handled routinely. Another benefit of plastic fiber is that its refractive index closely matches that of water, which enhances the coupling effect. The evanescent coupling effect can also be increased by increasing the surface roughness of the fiber, by creating more places for loss (scatter) to occur, while still preserving the fiber's transmission properties. The disadvantage of the plastic fiber is the lack of standard coupling devices to input the laser and feed the output into a data system. This problem could be fixed with appropriate hardware.

Fresnel Reflection Losses

Two probes were built using the principle of Fresnel reflection losses. The first probe used segments of quartz rods, arranged with a small air gap between each rod, Fig. 3.

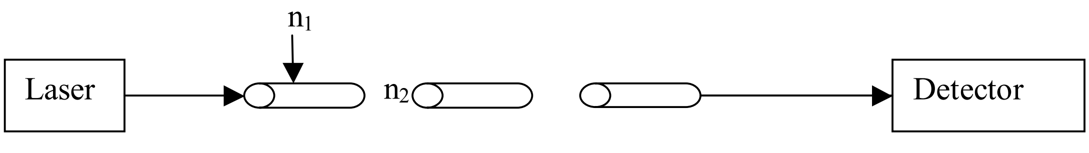


Figure 3 Losses occur at each n_1 to n_2 interface

The idea is, as the tank fills, the transition region between the rods switches from being filled with air to being filled with liquid. There is then a corresponding increase in transmission. At a glass/air interface the transmission loss is 4%. At each glass/water interface the transmission loss is only .5%. These losses are predicted by the Fresnel equations. This probe is easy to assemble and it can withstand moderately rough handling. The main problem with this design is that it is very difficult to get adequate power through the array of rods and through to the detector. This problem could be solved with better optical components.

The second design based on Fresnel losses used the plastic fiber again. This time small notches were cut into the fiber. The notches played the same role as the air gap in the segmented quartz rod probe.

Test Setup

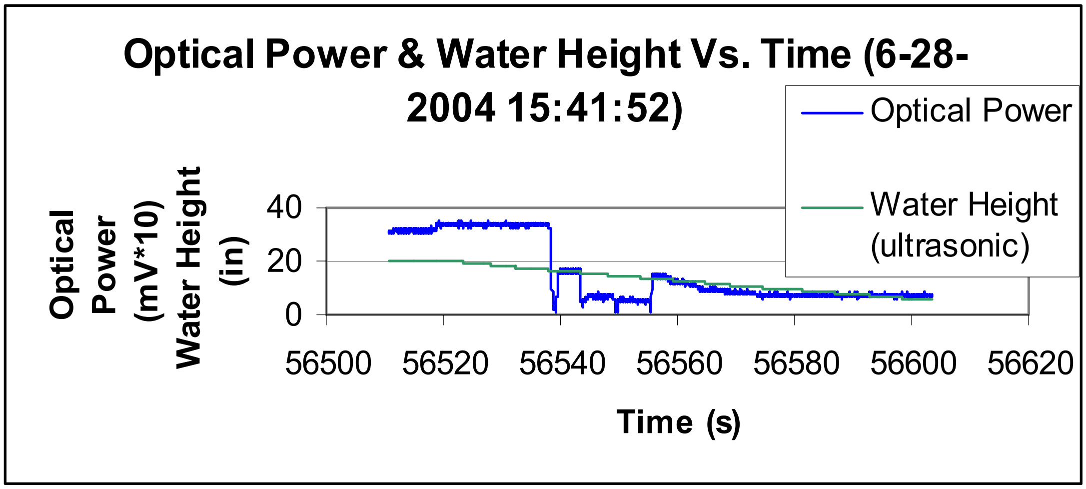
All of the probes were tested in water before they were tested in liquid nitrogen. A 3 feet tall water tank was provided that was equipped with a drainage device to allow tank level measurements as the tank was emptied and filled. The optical tank level measurements were verified by a sonic level meter, pressure sensor and flow meter. The LN2 was tested in a static configuration where the probes were placed in a full liquid nitrogen dewar.

Results

There were mixed results from all probes tested. Problems occured with low transmission, wetting of the probe's surface, and overall system construction. The results are summarized below.

The roughened plastic fiber showed approximately 10% decrease in transmission when submerged in liquid nitrogen, (LN2). Transmission increased back to pre-test levels when the fiber was first removed from the LN2. However, as the fiber returned to room temperature condensation and frost covered it. The condensation effectively resubmerged the fiber and transmission decreased again, making the sensor unreliable with repeated use. This would not present a large problem once the sensor is deployed in an enclosed LN2 tank, where temperature does not change so rapidly and water vapor is not available for condensation.

The data from the segmented quartz rod probe produces a step output, with a noisy section between each step that represents the turbulence as the gap is partially filled with liquid.



The notched plastic fiber also showed a step response in the data. Unfortunately it had the same condensation problems in LN2 as the roughened plastic fiber.

Conclusion and Recommendations

It appears that more work should be done with the plastic fibers. If a more stable probe and coupling setup were built, more accurate results could be obtained, especially in a more controlled temperature environment.

The segmented rod probed could be significantly improved by using better optics. The current quartz pieces are not polished on the faces, resulting in substantial loss at each interface. Gradient Index (GRIN) lens are available in the general cylindrical shape required and they would relay collimated light through the linear array with low scattering losses at the interfaces. The improved optics should reduce the overall signal to noise ratio of the probe.

Acknowledgments

I would like to thank everyone in TD72 for being helpful and supportive of this project. I give special thanks to: NASA Faculty Fellowship Program (NFFP), my NASA colleague, John Wiley, for being a great listener and encourager, Val Korman, Madison Research Corporation, for his daily guidance and ideas, Edwin Sutton, LB&B, for his fast and courteous technical support, and finally, to my UAH faculty advisor, Prof. Don Gregory, for the opportunity to participate in this program.

References

1. Hecht, Eugene, Optics, 2nd Edition, Addison-Wesley Massachusetts, 1990, p.170.
2. ibid p.107.
3. ibid p.99.