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A2_6 Conditions for Air to Cast a Shadow

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Abstract
Air is transparent and does not absorb or reflect much light, hence it is improbable to have a shadow. In this article, we determine the conditions under which air can have a visible shadow comparable to the shadow of glass. This is done with refraction, by changing air's refractive index to that of glass, $n = 1.5$. At a temperature of 0^oC, the air pressure needed to cast this shadow was found to be $1.57 \times 10^8\ Pa$, analogous to the pressure used in high-pressure hydraulic hoses [5]. These are thought to be reasonable conditions to see the shadow of air.

Introduction

Normally, air is translucent, which means that it cannot block light and therefore, cannot form a shadow. Shadows occur when a body prevents some of the light from an incident light beam to continue on in the initial direction. Transparent objects such as glass and air do not absorb or reflect very much light, but they can still interact with light through refraction and hence potentially cast shadows. In this article we discuss the conditions under which this is possible.

Theory

Refraction occurs when a light beam incident on an object passes through it and the light beam's direction is bent. If the direction is bent enough, the light that passes through the object will be angled away from the initial direction. As a result, we will have a dark spot - a shadow.

The condition for refraction and hence for the light to bend is for the index of refraction to differ from one location to the next. The refraction index is also thought as the ratio of the light's velocity in the two mediums. For example, air and glass are different materials and have different refraction indices and so when light passes through the glass, it bends at its surface since that is the point where the index of refraction differs. This is shown in Figure 1 and can be explained with Snell's law [1], where n_1 and n_2 are the indices of air and glass and θ and ϕ are the angles of incidence and refraction respectively.

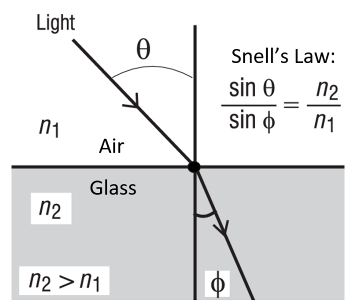

Figure 1: Refraction of light [1]

Uniform air cannot refract light and create shadows because its refraction index does not differ anywhere. However, when different regions of air have different indices of refraction, the air can indeed bend light away from its initial direction and create a shadow.

The refraction index of air can be changed by varying its temperature and its pressure. By changing its temperature, specifically by heating regions of air, the air expands, becoming less dense and light travels faster through those regions. Hence, warm air has a different refraction index than any regions of cold air (which are denser and light travels slower) therefore bending the light and creating shadows.

Equally, pressure variations can change the density of the air and hence cause differences in refraction indexes, leading to shadows.

The refractive index increases as temperature decreases and pressure increases as shown in,

$$n_2 = 1 + (n_1 - 1)\left[\frac{T_1}{P_1}\right]\left[\frac{P_2}{T_2}\right] \tag{1}$$

where n, T and P are the refractive index, temperature and pressure respectively. The subscript 1 notation represents colder, lower pressure regions of air, while the subscript 2 notation represents warmer, higher pressure regions.

It has been shown [3] that the reflectivity, R, of materials like glass and air depends solely on the refractive index, n, such that,

$$\mathrm{R} = \frac{(n-1)^2}{(n+1)^2} \tag{2}$$

and hence the percentage of transparency, T, of the shadow created can be found by,

$$\mathrm{T} = (1 - R) \times 100. \tag{3}$$

Results and Discussion

Glass has a refractive index of about 1.5 [4]. Using the refractive index of glass and Eq.(2) and (3), we found the reflectivity of glass to be 0.04 and the percentage of transparency, 96%. We can hence calculate the conditions needed for air to have a similar shadow with transparency 96%.

Air has a refractive index of 1.0003 [4], but by changing the temperature and pressure of a certain region of air, we can increase its refractive index to about 1.5, which is shown below.

We imagine a scenario of 2 different air mediums. Medium 1 is normal air with a refractive index of $n_1 = 1.0003$, a temperature of $T_1 = 20^oC = 293\ K$ and a pressure of $P_1 = 101325\ Pa$ (atmospheric). In order to raise the refractive index of medium 2 to $n_2 = 1.5$, we decrease the temperature and increase the pressure of the air in medium 2. By substituting values for n_1, T_1, P_1 and n_2 into Eq.(1), we are left with $\frac{P_2}{T_2} = 576365$. This means that for a temperature of $T_2 = 0^oC = 273\ K$ (for a cold winter day in Britain), the pressure needs to be $P_2 = 1.57 \times 10^8\ Pa$ for us to see the air cast a shadow of the same intensity as the shadow cast by glass.

Conclusion

The temperature and pressure conditions for us to be able to see the shadow of air as clearly as we would see the shadow from a glass were determined in this article. For an air temperature of 0^oC, the pressure of air needed was calculated to be $1.57 \times 10^8\ Pa$ (1570 bar). This is a very high pressure and it is comparable to the pressure used by high-pressure hydraulic hoses [5]. It is reasonably expected that a high pressure is needed to make normal air have a shadow since under typical atmospheric pressures, air is completely transparent.

References

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