The Lens Effect of Pressure Windows

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The lens effect of high pressure optical systems involving glass or quartz windows has been studied and found to be due to four primary causes. (1) Pseudo-lens effects due to temperature gradients following changes of pressure. (2) Bulging of the outer surface of the pressure window. (3) Pseudo-lens effect due to unequal distribution of strain in the window. (4) The difference in index of refraction of the material in the cylinder and that of the window combined with the bulging of the inside surface of the window. These effects are measured and methods for their correction outlined.

INTRODUCTION

THE lens effect of pressure windows or of the entire optical portion of a pressure system as produced directly or indirectly by pressures has been studied with the view to determine the nature of the effect and if possible how to prevent or at least to correct for such effects. These lens effects were encountered in an attempt to measure the index of refraction of materials under pressure and this study wts found necessary before many optical investigations could be successfully carried on.[1,2,3,4]

APPARATUS AND PROCEDURE

The apparatus employed is a combination pressure cylinder and observation chamber which is so constructed that the observation chamber is located at the end of the pressure cylinder. The main body A, Fig. 1, is machined from a single piece of steel, thus preventing the possibility of leaks in connections between the pressure cylinder and the observation chamber. The safety windows J prevent danger from flying materials in case the pressure windows F blow out. The temperature is controlled by circulating water from the thermostat through the water jackets which cover both sides of the assembly and are connected by the openings marked H in the diagram. Water is also circulated through the platins of the hydraulic press. The material under investigation is placed in the observation chamber L and the pressure is developed by forcing the piston B into the pressure cylinder with a hydraulic press. The pressure in the high pressure cylinder is determined as in previous work by the authors.

The two ends of the observation chamber are fitted with glass or fused quartz windows F, mounted against the window supports. The rubber plug E makes a tight joint around the end of the piston.

[1] Thos. C. Poulter, Phys. Rev. **35**, 295 (1930).
[2] Thos. C. Poulter and Robert Wilson, Iowa Academy of Science **37**, 299–302 (1930).
[3] Thos. C. Poulter and Harold C. McComb, Iowa Academy of Science **37**, 311–12 (1930).
[4] Thos. C. Poulter, Apparatus for Optical Studies at High Pressures, Phys. Rev. 40, 860 (1932).

A light source O and lens N is placed at one end of the cylinder and adjusted so as to pass parallel light through the optical system, consisting of the two windows and the liquid within the observation chamber. A straight wire filament incandescent bulb is placed at the principal focus of the lens N for a light source. For large converging lens effects, the lens P is removed and a screen is placed at the other end of the observation chamber and adjusted so as to give a clear image of the filament. For diverging lens effect or small converging effects, a converging lens of known focal length is placed between the end of the chamber and the screen. The focal length of the combination is measured from which the lens effect of the pressure system can be calculated.

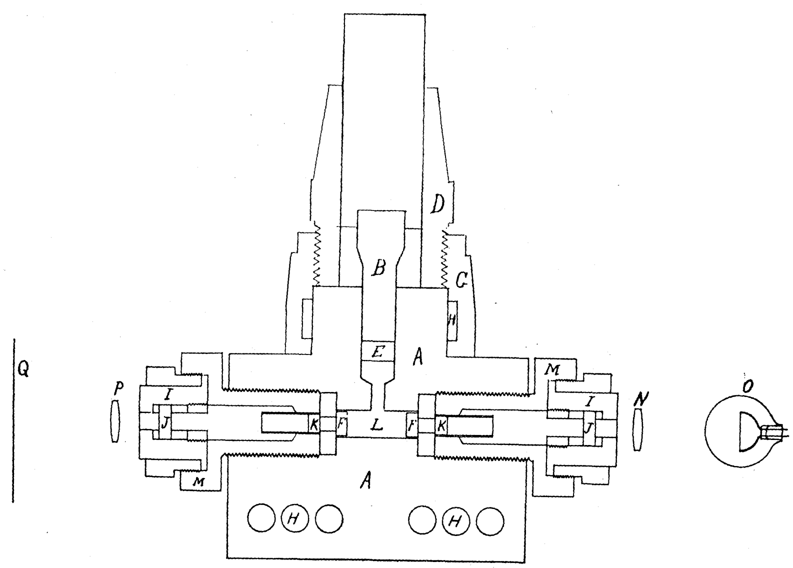

Fig. 1. Cross-section of pressure assembly and optical system drawn to scale.

Experimental Results

A large lens effect, being somewhat diffused at first but becoming sharply defined upon standing, is observed immediately following a pressure change. This is a diverging lens effect following an increase in pressure, and a converging lens effect following a decrease in pressure. These effects are of the order of magnitude that give a focal length of $+4$ cm or -4 cm. This value changes rapidly at first and becomes constant after standing for about five minutes. For a given pressure this constant value is the same regardless of whether the pressure has just previously been increased or decreased. A similar effect can be produced by rapidly changing the temperature of the observation chamber. If the observation chamber is rapidly heated by passing steam through the water jacket a converging lens effect is produced, whereas rapid cooling produces a diverging lens effect. If sufficient time is allowed following a pressure or temperature change (usually five minutes is sufficient) for the lens effect to come to a constant value, this value is always that of a converging lens if the system is under pressure.

If another window K is then mounted just outside each of the pressure windows and the intervening space filled with a colorless liquid having an index of refraction the same as that of the window, most of the lens effect disappears.

For determining the remaining lens effect a lens P of known focal length is placed at the end of the cylinder opposite the source of parallel light. The focal length of the combination is then measured from which the focal length of the pressure system can be calculated. Table I contains a typical set of values for windows 4 and 8 mm in thickness. Experiments were carried out

TABLE I. *P—Pressure in atmospheres;* F_1*—Focal length of the pressure system uncorrected;* F_2*—Focal length of the pressure system calculated from R;* F_3*—Focal length of the pressure system using liquid correction window;* F_4*—Focal length of the liquid correction windows;* R_1*—Radius of curvature of the outside surface of the windows, optical method;* R_2*—Radius of curvature of the outside surface of the windows, plaster-of-paris method.*

	4 mm window						8 mm window				
P	F_1	F_2	F_3	F_4	R_1	R_2	F_1	F_2	F_3	F_4	R
1	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞
2000	24.1	16.2	−50	−16.2	15.6	16.0	55.0	36.2	−105	−36.2	35.5
4000	21.6	15.1	−50	−15.1	14.4		47.0	30.0	−105	−30.0	29.3
6000	18.9	13.7	−50	−13.7	13.1	13.0	38.9	28.4	−105	−28.4	27.8
8000	18.6	13.6	−50	−13.6	12.9		38.0	28.0	−105	−28.0	27.3
10,000	18.4	13.1	−50	−13.1	12.7	13.0	37.0	27.4	−105	−27.4	26.6
8000	18.5	13.5	−50	−13.5	12.8		38.0	28.0	−105	−28.0	27.3
6000	18.9	13.7	−50	−13.7	13.1	13.0	39.0	28.5	−105	−28.5	27.9
4000	21.5	15.0	−50	−15.0	14.3		40.0	29.0	−105	−29.0	29.2
2000	24.0	16.2	−50	−16.2	15.6	15.5	52.0	36.0	−105	−36.0	35.3
1	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞
30,000	15.2	11.7	−50	−11.7	11.0	11.0					

on 4 and 8 mm glass windows and 4 mm fused quartz windows. The values were the same within the limits of experimental error for the glass and quartz windows so only one set of data is given. These values are for windows 12 mm in diameter and placed over a 6 mm hole in the window support. In order to check the curvature of the glass or quartz by a more direct method, the opening in the window support was filled with freshly prepared plaster-of-paris. Pressure was then applied and the plaster-of-paris allowed to set, thus leaving the impression of the curved surface of the window. After allowing it to harden thoroughly, the curvature was measured by means of a micrometer. The values for the radius of curvature as obtained by this method check to within less than 5 percent of the values obtained by the optical method. This corresponds to an error in measuring of less than 0.001 cm, which is as close as measurements can conveniently be made to a plaster-of-paris surface.

Discussion of Results

The nonexistence of a large pressure gradient in the oil used to transmit the pressure is definitely shown by the behavior of the optical portion of the system during, and for a few minutes following, a pressure change. During and immediately following a pressure change, the image of the filament through the pressure system is much less sharply defined than it is after standing for about five minutes. If one observes the contents of the observation chamber during a pressure change, a distinct turbulent flow of material from the pressure cylinder to the observation chamber can be observed. This flow is visible due to the difference in the index of refraction accompanying the temperature change on compression. The contents of the observation chamber again become homogeneous on standing. This turbulent flow is even more easily observed if some finely divided solid material is suspended in the oil. Such a flow of material precludes the possibility of any very large pressure gradient.

The lens effect of the pressure system is probably due to a combination of several effects, the most important of which are:

1. The pseudo-lens effect due to a temperature gradient and thereby a density gradient of the material under pressure following a pressure change. This gradient existed between the walls of the observation chamber and a line through the center of the chamber.

2. The bulging of the outside surface of the pressure window.

3. The pseudo-lens effect due to the unequal but symmetrical distribution of strain in the glass or quartz of the window. This is due to the window support exerting a force around the edge on the supporting surface and not over the center.

4. The bulging of the inside surface of the window together with the difference in index of refraction of the window and the material under pressure.

The largest of these effects and the easiest one to correct for is the pseudo-lens effect following a change in pressure. At first thought it might appear as though this were due to a pressure gradient rather than a temperature gradient. If it were a pressure gradient it would likely extend between the center of the observation chamber and the windows. Any lens effect thus produced would be likely to be of the reverse nature, namely, a converging effect following an increase of pressure and diverging effect following a decrease in pressure. Furthermore, if it were a pressure gradient due to the materials becoming stiff under pressure, it would be most pronounced at the higher pressures, whereas it is much greater at pressures below 2000 atmospheres. That it is due to a temperature and thereby a density gradient is suggested by the fact that as soon as sufficient time is allowed for constant temperature to be established, the effect disappears. This is further confirmed by the fact that if the observation chamber is rapidly heated by running steam through the water jacket, an effect is produced similar to that produced by a decrease in pressure. Rapid cooling produces the same effect as an increase in pressure. The temperature of the material in the cylinder is suddenly increased due to compressibility during an increase in pressure. Since it is then at a higher temperature than the walls of the observation chamber, the material in contact with the walls is cooled first, producing a greater density around the outside than that through the center, hence the diverging effect. The reverse is true following a decrease in pressure. Since this effect completely disappears within five to ten minutes following a pressure change, it is automatically corrected for by allowing that time before making observations.

The next largest effect and also the next easiest to correct for is that of the bulging of the outer surface of the window. This effect is largely corrected by placing a liquid of about the same index of refraction as the window in contact with its outer surface. The radius of curvature of the outside surface of the pressure windows is determined in the following manner. The pressure windows and the intervening pressure liquid produces a lens of focal length F_1 whose thickness is the distance between the two outside surfaces of the windows. Now there is placed a layer of liquid on both curved surfaces which produces two diverging liquid lenses at the ends of the pressure system. The focal length of this combination F_3 is measured from which the focal length F_4 of the liquid correction windows alone can be calculated. Since we know the focal length F_4 of this pair of diverging liquid lenses and the distance between their curved surfaces C, their curvature, and hence, the radius of curvature of the outside surface of the pressure windows, can be calculated by means of the following equation

$$\frac{1}{F_3} = (\mu - 1)\left\{\frac{2}{R} - \frac{(\mu - 1)C}{\mu R}\right\} + \frac{1}{F_1}$$

in which μ is the index of refraction of the liquid used as correction window.

At pressures of 30,000 atmospheres, glass and quartz windows 4 mm in thickness will bend to a radius of curvature of as small as 11 cm. Glass windows will withstand such bending sometimes as many as five to ten times without apparent damage. Windows made of fused quartz are usually cracked after one or two such pressure runs.

The third and fourth effects are small as compared to the first two and are much more difficult to measure individually. The third could be measured by measuring the change in focal length of the system as materials of different indices of refraction are used in the observation chamber, if the effect of the pressure upon the index of refraction of such liquids were known. Since very little or no such data are available, usually the third and fourth effects are measured together with that due to any other cause if there be such. The magnitude of these latter two effects is indicated by the difference in focal length of the pressure system F_1, and F_2 the focal length as it would be if these factors did not enter.

If a liquid of the proper index of refraction is selected to place in contact with the outer surface of the pressure windows, an optical system can be obtained with almost no lens effect. If the remaining lens effect, after the first two have been corrected for, is that of a converging lens, a liquid of index of refraction greater than that of the window is required, whereas if it is a diverging effect, a liquid of index of refraction less than that of the window is required. In this way optical pressure system have been obtained whose focal length only changes from ∞ to 10 meters in changing from 1 to 30,000 atmospheres.

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