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1

THE EFFECT OF SURFACE CONDITIONS ON THE INTENSITY AND ANGULAR DISTRIBUTION OF SUBMARINE DAYLIGHT.

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IT is generally recognised that weather conditions have a large effect on the percentage of incident daylight that is cut off by the surface of the sea. When the water is entirely unruffled by wind only a small percentage of the light is reflected, the exact proportion being calculable by Fresnel's formulae if the angular distribution of the incident light is known; the remainder is transmitted, so that the surface loss amounts to some 6·5 per cent. with diffuse daylight, falling to about 2 per cent. for vertical sunlight. When, however, the surface is ruffled by waves, especially if their tops are broken by the wind, the loss is found to rise to 30 or 40 per cent. Even so large a loss as 30 per cent. is not of outstanding importance in measurements at considerable depths, as in average water it would only correspond to the effect of an increase of depth of some 2 metres, but if the surface conditions have also an appreciable effect on the average obliquity of the submarine light they will affect the vertical extinction coefficient, and so cause greater changes in the illumination at any level.

The angular distribution of the light under water is evidently of great importance, as it affects, not only the vertical extinction coefficient, but also the ratio of the total illumination at any point (as measured by a spherical photometer surface sensitive to light from all angles) to the vertical illumination, as usually measured with a horizontal plane photometer surface. As this total illumination is the most important factor in photosynthesis, recent direct measurements of the angular distribution of the illumination are of great value (P e t t e r s s o n *et al.*, 3), since they enable the ratio of the total to the vertical illumination to be found. They have so far, however, only been carried out under calm conditions, and it is worth while considering what effects we should expect to be produced by wind and waves.

The Measurement of Surface Losses.

It is usual to take the illumination on the upper surface of a horizontal plane as a measure of the submarine light. In order that this may be a clearly-defined quantity it is necessary that the surface should be freely exposed to all rays coming from any point above the horizon, and that it be affected by oblique rays in accordance with the cosine law. This means that any rim surrounding the surface should be as low as possible in comparison with its diameter, and that if possible a matte surface should be used. Unfortunately, the diffusing and transmitting properties of any roughened surface are entirely altered by overlying water, so that for marine measurements — even for air measurements in the presence of rain or spray — a polished surface is preferable. We can make suitable correction for reflection losses for light of any given angular distribution by means of Fresnel's formulae (4). For glass of refractive index 1·51 the correction for pure sunlight of 30° altitude, or for the light from a uniform sky, amounts to about 6 per cent., falling to zero for vertical sunlight (since the photometer is standardised in perpendicular light), and rising to large values for low-angle sunlight.

Since the rectifier photo-cell, which is now generally used for marine work, must be mounted behind a strong glass window in a water-tight case it is difficult to avoid excessive screening of low-angle light by the rim if we use a clear window and employ the sensitive surface of the cell as the receiving surface. Moreover, as there are several polished surfaces involved reflection corrections for oblique rays become much more important and difficult to calculate, and, when such a photometer is submerged, it is totally insensitive to any ray making an angle greater than 48·5° with the perpendicular, as this will undergo total reflection at the inner surface of the glass window, and so fail to reach the cell. Just below a perfectly smooth water surface there will be no rays making an angle with the vertical greater than 48·5°, but in the presence of ripples, such rays will occur, so that such a photometer is useless for measuring the surface loss of light.

In order to avoid this loss of oblique rays we must use an opal diffusing glass as a receiving surface, allowing the light transmitted and scattered by the opal to act on the cell. This opal glass (which must be polished on its upper side, at least) must be mounted above the window and any colour filter used, the intervening spaces being kept filled with water to maintain constant reflection losses between the opal and the cell. Alternatively, we may use an opal window, the colour filters being mounted inside the case and changed by some such device as that used by Utterback (6).

For narrow-angle measurements, as in Pettersson's recent work, the photometer is not required to be sensitive to oblique rays, and the average obliquity of the rays passing through the colour filter is small and sensibly constant, so that an opal is unnecessary, and merely reduces the sensitivity.

The reading of a photometer consisting of a sensitive cell mounted behind a diffusing glass depends on the illumination reaching the diffusing layer in the interior of the glass. When we lower such an instrument into water the conditions at the polished upper surface of the glass are changed, and appropriate corrections must be made for the change in the loss of incident light and for the reduction in internal reflection of light scattered back by the diffusing layer inside the glass. We may treat these two sources of error separately, by multiplying the photometer reading by the product of two factors, which we may call the "external reflection factor" and the "internal reflection factor", respectively (1).

Considering first the external reflection factor, we must remember that when the photometer is standardised in air, either by exposure to a known intensity of illumination normal to the surface or by comparison with another photometer in diffuse or mixed daylight, some of the light striking the polished upper surface is lost by reflection, the percentage being about 4 for perpendicular light, and nearly 10 for perfectly diffuse light or for light at 60° angle of obliquity, i.e., for sunlight of 30° altitude. For marine work it is generally sufficiently accurate to treat mixed daylight as being equivalent to perfectly diffuse light and to use the constant for the photometer corresponding to the 10 per cent. loss. The presence of a shallow layer of water above the glass reduces this loss slightly, but as it also increases the loss of back-scattered light (see next paragraph) its nett effect is small. When, however, the photometer is used to measure the illumination in the water (as distinct from that in the air above it) the reflection loss is appreciably reduced.

The internal reflection factor is the more important of the two, as, when the photometer is in air over 40 per cent. of the light reaching the diffusing layer is scattered back, and much of this strikes the upper surface at an angle greater than the glass-air critical angle, and undergoes total internal reflection, thus returning to the diffusing layer and contributing to its illumination and hence to the photometer reading. When the photometer is submerged most of this internal reflection is eliminated, and if the depth of immersion exceeds the radius of the diffusing glass total reflection from the water-air surface does not affect the photometer, so that the sensitivity is reduced. It would appear from such laboratory tests as have been made that the nett effect of the two corrections is to reduce the sensitivity by about 8 per cent., so that the constant found for the photometer for diffuse light in air should be multiplied by 1·09 when the photometer is used under water. As this correction is comparable with the surface loss it is evidently of importance, and further determinations of its value may be desirable.

Many of the early estimates of surface loss were affected by errors due to the neglect of one or both of the reflection correction factors, or by the use of photometers insensitive to oblique rays. Moreover, the measurement of surface loss presents certain practical difficulties. If the waves are large enough to affect the ship it is very difficult to keep the photometer at even an approximately constant small depth of immersion, and the rapid variations in the sub-surface illumination render the determination of the average value difficult. Care must also be taken that the variation in the shading by the ship according as the photometer is just above or just below the surface, does not introduce appreciable errors.

It is customary to estimate the surface loss by extrapolating the illumination curve up to the surface from the shallowest level at which reliable measurements can be made under the existing conditions. In this way values have been obtained ranging from a few per cent. in calm water to over 40 per cent. in rough weather.

Powell and Clarke (5) have made a special study of the problem, and have greatly reduced some of the difficulties by suspending their photometers from a floating tubular structure designed to cast very little shadow. They also used an inverted photometer a few metres above the surface to measure the reflected light, and, by lowering it just below the surface found the light scattered back by bubbles or suspended matter in the upper layers.

As the percentage reflected from a smooth water surface rises with the obliquity of the incident light it is a minimum — about 3 for red and 4 for violet — with high sun, rising to 6 or 7 for cloudy conditions or for medium angle sun, and up to 20 with low sun. It is also increased by roughness of the surface, but, according to Powell and Clarke, the increase in reflection so caused is much less than the surface loss of submarine light occurring under such conditions. These authors obtained evidence that the "surface loss" as usually found includes, not only the loss at the actual surface, but also the effect of a highly absorbing layer, often about 1 metre thick, just below it. They would seem to be justified in claiming that this effect is due to bubbles carried down by breaking wave tops.

It is a little difficult, however, to account for the loss of radiation. If there is no actual absorption of radiant energy the flux density on a horizontal up-turned photometer above the surface should be equal to the sum of the flux densities on an up-turned submerged photometer and on a down-turned photometer measuring the reflected light. In other words the incident vertical illuminations should equal the sum of the transmitted and reflected vertical radiations, and no amount of scattering should alter this relation. Now Powell and Clarke found that when under rough conditions the transmitted vertical radiation was about 70 per cent. of the incident the reflected radiation was only about 10 per cent., leaving 20 per cent. to be accounted for. If we assume that most of this loss occurs in a layer 1 m. thick just below the surface we must assign to this layer an extinction coefficient 2 to 3 times as great as the average for deeper layers, this excess being produced by the roughness of the water. Moreover the excess extinction must be due to absorption, and not to scattering alone.

The diffusing layer postulated by Powell and Clarke must differ from that in an opal glass in two important respects. In the first place the individual bubbles are probably large compared with the wave length of light, so that the proportion of the illumination scattered in any direction is governed by the laws of reflection and refraction, and not by that of scattering by small particles, and, secondly, only a small fraction of the illumination undergoes multiple scattering in the layer. Moreover, the layer is so thick that appreciable true absorption occurs.

If we estimate the proportion of the incident light reflected and refracted in different directions by a spherical air bubble we find that over 50 per cent. is deviated through angles between 20° and 60°, only about 1 per cent. being deflected through more than 90°. This explains the small effect of the bubbles on the reflected light. Their chief effect must be to add to the diffusion caused by the rough surface above them, so that we should expect that under rough weather conditions the average obliquity of the sub-surface illumination would be considerably increased. This would increase the vertical extinction coefficient in the layer by adding to its effective thickness, though we should hardly expect such a large result as a doubling or trebling of the extinction as would be required in order to produce the given reduction in a layer only 1 m. thick. It is more reasonable to assume that the increased obliquity persists to considerably greater depths, though Clarke's results are in opposition to this view.

The evidence as to the effect of depth on the average obliquity is not very satisfactory. Atkins and Poole concluded, as a result of their work, that the angular distribution of the incident light and the condition of the water surface had little effect on the vertical extinction coefficient at depths below 10 m. They considered that the average obliquity at the deeper levels was chiefly governed by a balance between the effects of absorption, which by filtering out the more oblique rays reduces the average obliquity, and scattering, which increases it. The few results that they obtained with vertical or inverted photometers indicated that the ratios of the horizontal and of the back-scattered to the vertical illumination were approximately constant at different depths. On the other hand the reduction in the vertical extinction coefficient which was found in most (though not in all) of their series might be taken as evidence of the reduction of obliquity with increasing depth, though this is unlikely to be the sole cause of the effect.

Clarke (2) concluded that in western Atlantic waters the average obliquity generally increased with depth, whereas Pettersson's most recent work, which is by far the most reliable that has yet been done on the subject, shows clearly that the average obliquity at 10 m. is less than that at 5 m. under a calm surface with bright sun in Swedish waters.

It is evident that further work on the subject of the angular distribution of submarine light under various conditions of surface and of surface illumination is very desirable, but pending the results of such work we should appear to be justified in assuming that the chief effect of surface disturbance is to increase the average sub-surface obliquity, and hence the vertical extinction coefficient in the shallower layers, the obliquity gradually returning to its equilibrium value in deeper water, as determined by the balance of the effects of absorption and scattering by such suspended matter as may be present.

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