XIV.—CONCERNING THE OPTICAL QUALITIES OF SOME MICROSCOPES MADE BY LEEUWENHOEK. 535.821

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Two Plates.

The subject of this contribution is the optical qualities of some microscopes made by Antony van Leeuwenhoek. I have been able to examine the lenses of two brass microscopes of the usual form, one of which is in the possession of Miss A. S. M. Haaxman at The Hague, while the other is the property of the Netherlands Historical Science Museum in Leiden and is exhibited there; moreover, I have examined the only surviving specimen of the *aalkijker*, or aquatic microscope, with its five lenses, the property of the State, which is also in the above-mentioned museum. Finally the museum contains one more microscope, in which, however, the lens is missing, of which I shall give some particulars below. To both the Director and Vice-Director of the museum and to Miss Haaxman I wish to express my great thanks for having allowed me to make an examination of these valuable historical instruments.

The three microscopes of the usual type are of especial interest, as they all come from the property of the Haaxman family, who are direct descendants of Leeuwenhoek's eldest sister Margaretha, so that there can be no doubt of their authenticity. The *aalkijker*, and the five lenses contained in a leather case are also by the hand of Leeuwenhoek himself, as Crommelin was able to prove with a probability bordering on certainty (1926, pp. 12–15; 1932, pp. 216–17) on the ground of dates supplied by Haaxman (1875, pp. 34–6).

Although Leeuwenhoek's microscopes from the very beginning raised a widespread interest and admiration and much has been written about them, little has been said about their optical constants, which are the chief reason for their great value. This may be partly due to the fact that Leeuwenhoek maintained a certain amount of mystery on the subject of his lenses and gave no one any opportunity of examining them. Moreover, he could seldom be persuaded to part with one of his microscopes to anyone else (Folkes, 1724, pp. 450–1; Uffenbach, 1754, p. 358; Huygens, Œuvr. compl. IX,

p. 38 ; Dobell, 1932, p. 313). He only sent descriptions and drawings, never a microscope or an object, to the Royal Society in London, although he communicated most of the results of his research to them. It was not till after his death that his daughter Maria sent a box containing 26 microscopes to the Royal Society. Folkes (1724, pp. 450–1), who describes this legacy, only says : " The glasses are all exceedingly clear, and shew the object very bright and distinct, which must be owing to the great care this gentleman took in the choise of his glass, his exactness in giving it the true figure."

Several years later Baker examined the lenses of the same microscopes (1740, pp. 503–19 ; 1764, p. 436) and found that their magnification varied from 40 to 160 diameters at a distance of 8 inches, which corresponds to a magnification of about 50 to 200 diameters at the usual distance of 10 inches. The focal length of these lenses varied from $\frac{1}{5}$ to $\frac{1}{20}$ inch (= 5 to $1\frac{1}{4}$ mm.).

Two years after the death of his daughter Maria, on May 29th, 1747, Leeuwenhoek's microscopes and other lenses from his estate were put up to auction (a copy of the catalogue exists, *inter alia*, in the library of the society " Natura Artis Magistra " at Amsterdam)—altogether several hundred pieces (van Seters, 1933, p. 4574). Unfortunately only a few of all these pieces have been preserved and of these only the microscope in the collection of the University of Utrecht has been optically tested, first by Harting (1850, pp. 41–4 ; 1866) and later, with identical results, by van Cittert (1932 : 1933 [1], [2] ; 1934 [1], [2] ; *cf.* van Albada, 1934). The results of van Cittert's examination are included for comparison in the last column of the table in this article, p. 181.

The three small microscopes at my disposal deviate in no way from the usual construction (see fig. 1), so that concerning their arrangement I may refer to descriptions already published (Folkes, 1724, pp. 449–50 ; Baker, 1764, pp. 434–5 ; Harting, 1850, pp. 41–5 ; Haaxman, 1871, pp. 22–4 ; 1875, pp. 36–7 ; Mayall, 1886 ; Disney, Hill, and Watson Baker, 1928, pp. 160–1 ; Crommelin, 1932, pp. 215–6 ; Dobell, 1932, pp. 328–30 ; van Cittert, 1934[1], pp. 14–16). They are constructed in the simple manner characteristic of Leeuwenhoek, but it can be seen that to Miss Haaxman's specimen the most care has been devoted.

One particular should be mentioned, that in the specimen M8a a hole has been bored (about $1\frac{1}{2}$ mm. in diameter) in the little block in which the focusing screws work, running parallel to the long focusing screw. This hole was obviously intended to contain a glass capillary tube for studying the aquatic micro-organisms.

The pitch of the screw which regulates the distance between the object and the lens is the same in all specimens, and also the same as that of the long screw set at right angles to it. As in the Utrecht specimen (van Cittert, 1932, p. 1062 ; 1934[1], p. 14), there are fully eleven spirals to 1 cm., a very coarse thread for the purpose of focusing the object to fractions of millimetres.

The lenses are mounted between two brass plates, of which the measurements are as follows: in Miss Haaxman's specimen, 40 × 18 mm.; in No. M8a of the Netherlands Historical Science Museum 41 × 17 mm.; and in No. M8aa, 46 × 22 mm. In one of the microscopes of the museum (No. M8aa of the catalogue) the lens is, as has already been stated above, unfortunately missing.

Before proceeding to discuss the optical constants of the lenses, I must say a few words about the *aalkijker,* or aquatic microscope, an instrument for observing the circulation of the blood in the caudal fin of a fish, the only specimen extant of this model of instrument made by Leeuwenhoek.

The original construction of the *aalkijker* is minutely described and drawn by Leeuwenhoek himself in a letter to the Royal Society (Epistola 66, 1689) and later by both Harting (1850, p. 380) and Haaxman (1871, p. 24; 1875, pp. 37–8). The specimen in the museum (see fig. 2) differs in several respects from the one described by Leeuwenhoek.

In the first place, in the surviving instrument, the spring which keeps the glass tube in its place is made of one piece, and is of a more elaborate form than in the original drawing. Moreover, it is considerably shorter, thereby avoiding the inconvenience of intercepting the light.* Moreover, the arrangement for focusing the lens has been changed. This is managed by a winged nut which brings the brass plate holding the lens nearer to the glass tube in which the object is contained. A third discrepancy is that the lens is fixed to the instrument in a different way. In the original model the lens, mounted between two brass plates as in the ordinary microscopes, had to be attached to the instrument by a screw. In the specimen in the museum there are five lenses contained in a red morocco case, upon which is written in ink: "Anth. van Leeuwenhoek." These lenses are very simply mounted between two plates of sheet-brass. They are inserted into a vertical dovetail at the top of the instrument until the lens is brought before an opening provided for the purpose.† This enables the lenses to be changed much more quickly than could be done with the original construction.

In spite of the fact that this improved construction of the aquatic microscope, as far as we know, was never published by Leeuwenhoek, it became known and was copied by some contemporaries. In the Netherlands Historical Science Museum there is an instrument made by Johan van Musschenbroek (No. M3: Crommelin, 1926, pp. 13, 31) which only differs from Leeuwenhoek's specimen in small details, and in the museum at Norwich Castle there is a similar instrument constructed by Edmund Culpeper (Clay and Court, 1932,

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* The "facsimile" reproduced by Baas Becking (1924, p. 553) does not seem to me to be usable, as the spring goes up so high that it intercepts the light on the lens.

† It should be pointed out that the five lenses found in the red case do not fit into the instrument well; only one of the five (lens II, a plano-convex one) can be inserted into the dovetail so that the lens comes in the middle of the opening designed for it. This makes it doubtful whether the instrument and the lenses, although both were found in the Kamerlingh Onnes-Laboratory, originally belonged together. There is, in my opinion, no reason to suppose that the five lenses in the case are not made by the same maker, as both the material used and the way of mounting are identical.

pp. 36–7). The method of mounting lenses between two thin brass plates was also applied in the same way by Johan van Musschenbroek, as may be seen in a microscope made by him, which is found in the " Court Collection " in the Science Museum in London (Clay and Court, 1932, pp. 38–9). There is, however, no possibility that the lenses in the Netherlands Historical Science Museum can have belonged to Musschenbroek's *aalkijker*, as they do not fit into this instrument.

The results of my optical examination of the lenses are collected in the accompanying table. There we see in the successive columns the data for the two microscopes in the Netherlands Historical Science Museum (indicated by their numbers in the catalogue M8a and M8aa), for the specimen belonging to Miss Haaxman, for the five lenses of the *aalkijker*, and finally the results of van Cittert's research, by way of comparison.

These results lead to the following remarks :

1. The *shape of the lens* in four of the specimens examined proved to be plano-convex. The plano-convex lenses have the convex side turned towards the object. In the Leeuwenhoek literature this shape is never mentioned as being found in his microscopes ; the Utrecht specimen has a biconvex lens (Harting, 1850, p. 44 ; van Cittert, 1933[1], p. 194 ; 1933[2] ; 1934[1], p. 14). The contemporaries of Leeuwenhoek did not even mention the possibility of plano-convex lenses being used by him ; there only was considerable discussion as to whether he used ground lenses or glass drops (Folkes, 1724, p. 449 ; Baker, 1743, p. 7, footnote).

2. The diameter of the openings in the brass plates which form the *diaphragm of the lenses* differs considerably. Probably Leeuwenhoek made them larger or smaller according to whether the object could be best examined with light of a greater or smaller aperture (Baker, 1740, p. 504–5). For the diaphragm on the object side of lens IV of the *aalkijker* no measurement can be given, as the plate containing the lens is damaged.

3. The *magnification* was determined at the usual distance of 25 cm. by measuring the image directly.

4. The *diameter of the field of view* was directly measured by means of an object micrometer of Zeiss. For obtaining the precise value the eye should be laid against the lens, which can be done approximately in the microscopes, but not with the lenses of the *aalkijker*, as these are mounted so as to protrude at the side of the object, while on the eye side a kind of cup is formed. Leeuwenhoek applied a similar mounting of the lenses with a hollow on the eye side in his second model of *aalkijker* (Epistola 66, pp. 197–8) ; the interpretation of this arrangement has given rise to confusion, as it was erroneously supposed that the cup-like hollow represents a Lieberkühn mirror (van Seters, 1933, p. 4574). In the lenses of the *aalkijker* here described an error of this kind is impossible, as the lenses only fit into the instrument when the convex side of the brass mounting is turned towards the object.

5. The *numerical aperture* was determined with a Metz apertometer made by the firm of Leitz.

TABLE I.— RESULTS OF THE OPTICAL EXAMINATION OF LEEUWENHOEK'S LENSES.

	M8a	M8aa	Property of Miss Haaxman	*Aalkijker*					Data of van Cittert
				I	II	III	IV	V	
Shape of the lens	Biconvex.	—	Biconvex.	Plano-convex.	Plano-convex.	Plano-convex.	Plano-convex.	Biconvex.	Biconvex.
Diameter diaphragm object side	0·7 mm.	1·4 mm.	0·9 mm.	1·8 mm.	1·9 mm.	1·2 mm.	—	1·1 mm.	0·5 mm.
Diameter diaphragm eye side	0·6 mm.	1·2 mm.	0·9 mm.	1·2 mm.	1·5 mm.	1·0 mm.	1·0 mm.	0·4 mm.	0·8 mm.
Magnification	100 ×	—	90 ×	32 ×	50 ×	50 ×	65 ×	150 ×	270 ×
Diameter field of view	65 mm.	—	135 mm.	60 mm.	70 mm.	65 mm.	50 mm.	45 mm.	70 mm.
Numerical aperture	0·13	—	0·12	0·08	0·13	0·08	0·12	0·15	0·4
Resolving power	4μ	—	4μ	6μ	5μ	5μ	4μ	$3{\cdot}1\mu$	$1{\cdot}4\mu$
Thickness of the lens	1·80 mm.	—	1·05 mm.	1·25 mm.	1·60 mm.	1·60 mm.	2·00 mm.	1·80 mm.	1·1 mm.
Focal length	2·5 mm.	—	2·8 mm.	8 mm.	5 mm.	5 mm.	3·8 mm.	1·7 mm.	1 mm.
Radii of curvature of the lens	2·5 mm.	—	2·8 mm.	4 mm.	2·5 mm.	2·5 mm.	1·9 mm.	1·7 mm.	0·75 mm.
Condition of the lens	Good.	Missing.	Good.	Good.	Good.	Good.	Good.	Damaged.	Damaged.

6. The *resolving power* could be measured by means of a couple of test-plates, which Dr. C. A. Crommelin was kind enough to have prepared for the purpose at the Kamerlingh Onnes-Laboratory. These are glass slides, upon which, like Nobert test-plates (Crommelin, 1934), a system of lines at a certain distance from one another have been engraved with a dividing machine. They only differ from Nobert test-plates in that the distance between the lines is larger. This provided test objects with a line distance of 100, 50, 25, $15\frac{1}{2}$, $12\frac{1}{2}$, 10, 6, 5, 4 and $3\frac{1}{10}\mu$ respectively. The Nobert test plate in the Netherlands Historical Science Museum continues this series, the coarsest line distance being about $2\frac{3}{10}\mu$. The numbers in the table indicate which groups of lines were still resolved ; they indicate thus in a sense the upper limit, as the true resolving power of the lenses lies between this value and the value of the following group.*

7. The *focal length* was not measured, but calculated by the formula $f = \frac{250}{m-1}$ mm., in which f is the focal length and m the magnification.

8. The *radii of curvature* of the lenses were calculated from the formula $\frac{1}{f} = (n - 1)\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$, in which f is the focal length, n the refractive index of the glass, and R_1 and R_2 the radii of curvature. Here it was assumed that glass with a refractive index of 1·5 was used and further that in the biconvex lenses the radii of curvature were the same on both surfaces.

9. Lens V of the *aalkijker* is seriously damaged on the object side which protrudes considerably, consequently a part of the field of view does not give a clear image, but in the rest of the field the resolving power is not interfered with.

Finally we add a few words about the *brass forceps* illustrated in fig. 1, which is in the possession of Miss Haaxman. According to the owner, this little instrument has always been with her microscope,† so that there was reason to believe that it had been made by Leeuwenhoek. All doubts on the subject were dispelled in my opinion, when the carpenter-custos of the museum, J. H. van Niel, pointed out to me that in the portrait of Leeuwenhoek painted by Verkolje, a copy of which hangs in the museum, similar little implements are painted. In the celebrated mezzotint portrait by the same artist, moreover, a similar object is seen to lie at the corner of the table. By comparison of fig. 1 and the detail reproduction of the painted portrait in fig. 3 we can convince ourselves of the identicality of the two forceps.

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* The values which were found for the numerical aperture and the resolving power do not agree, either in my research or in van Cittert's data, with the formula given by Abbe : $A = \frac{\lambda}{2b}$, in which A represents the aperture, λ the wave-length of the light used (for daylight a mean of $0{\cdot}540\mu$), and b the smallest distance at which two points or lines can be separately seen. This formula only applies to systems with better optical qualities.

† It should be pointed out that Dobell considers this object as a pair of compasses (1932, p. 346, note 2).

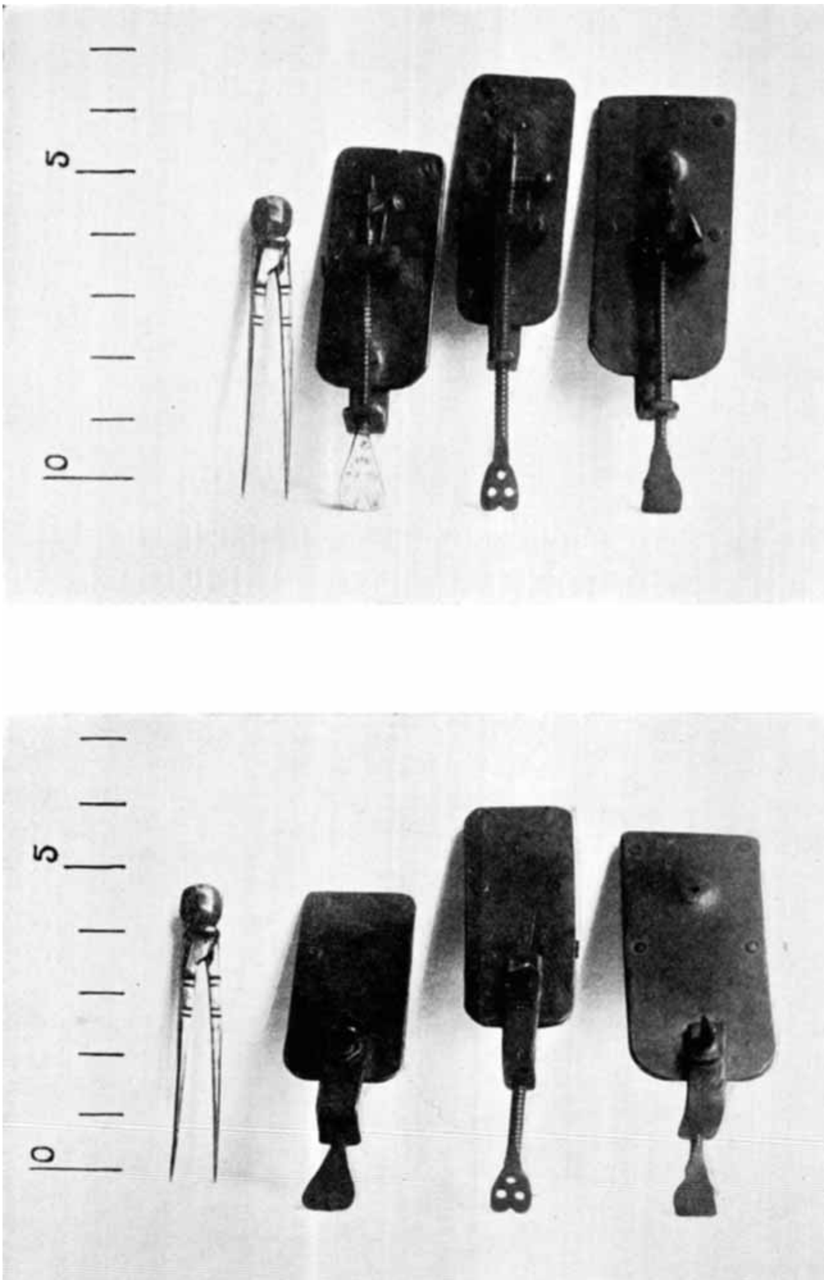

Fig. 1.—Forceps and microscopes by Leeuwenhoek. Above: object side; below; eye side. From left to right: forceps; microscope belonging to Miss Haaxman, the Hague; microscope M8a belonging to the Netherlands Historical Science Museum; M8aa (without lens) also belonging to the museum.

[*To face p.* 182.

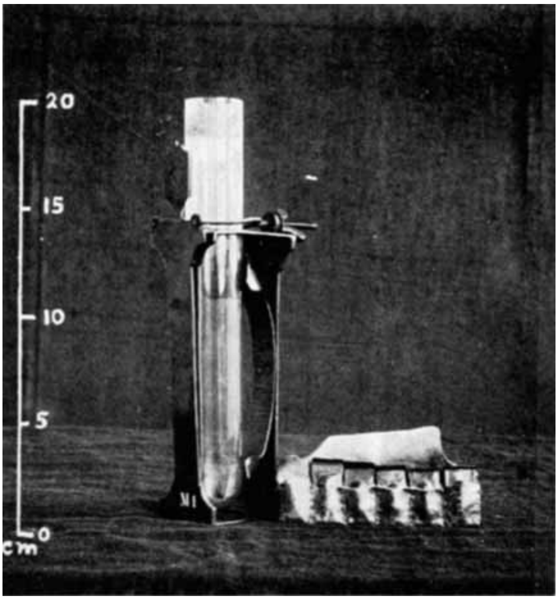

FIG. 2.—*Aalkijker* or aquatic microscope by Leeuwenhoek (the glass tube is new) and leather case with five mounted lenses. In the left-hand compartment of the case an unmounted lens was still present in 1875. (*Neth. Hist. Science Museum Leiden.*)

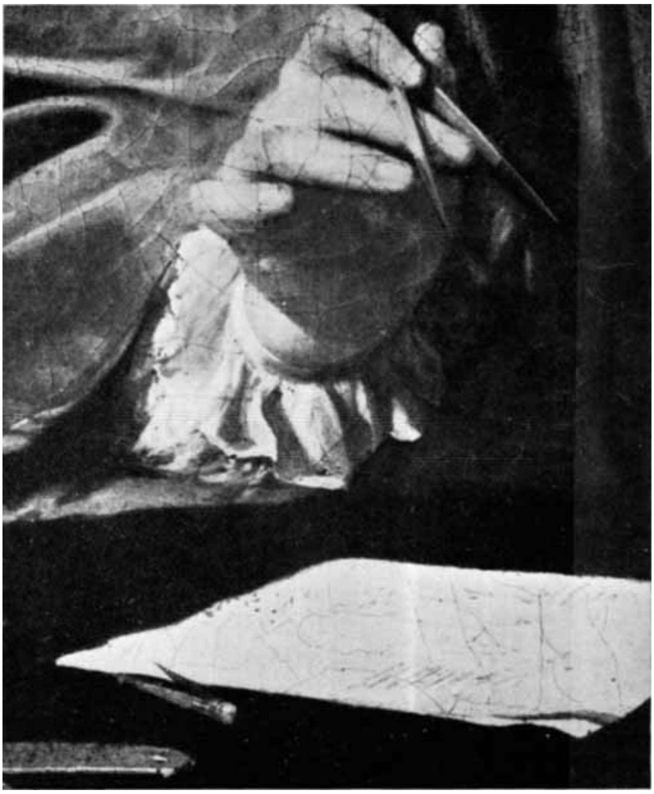

FIG. 3.—Detailed photograph of the portrait of Leeuwenhoek painted by Verkolje. The instrument that Leeuwenhoek holds in his hand is provided with steel points, the forceps lying on the table are made entirely of brass, except the axis, which is of white metal. (*Jan Verkolje pinx. Rijksmuseum, Amsterdam.*)

To face p. 183.]

The instrument, which is only 4½ cm. long, has every appearance of having been made by an amateur and is as roughly finished as Leeuwenhoek's microscopes are. With the exception of the iron axis it is made entirely of brass. The construction is the same as of a compass, but it cannot be used as such, the points being much too blunt. Considering the nature of Leeuwenhoek's researches, it is most natural to suppose that he used it as a forceps.

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