High-Speed Photography in the Development of a New Form of Pulverizer

PAPER J—2

By ROLAND JACKSON and D. V. SIMPSON

Normal methods of exploration of the performance of a new pulverizer gave anomalous results that were not easy to explain. High-speed photographs of the flow of particles through the pulverizer revealed directly many of the causes of these anomalies. A new design of the mill based on these findings has been made and high-speed photography is being used as a tool in the investigation of its performance. The high-speed photography technique is straightforward, using a Fastax camera at speeds up to 1000 frames/sec. The major problems have been inaccessibility of subject and provision of sufficient light, because the material being pulverized was coal.

Although we in the B.C.U.R.A. have been studying the pulverizing of coal for many years, we had not considered, until comparatively recently, that high-speed photography could assist this type of research to any considerable extent. We have now found that this method can prove extremely valuable, and is not particularly difficult to apply.

The present paper summarizes some of our experiences in one branch of this work. Although no new photographic developments have been made, we feel that a review of our problems may be of interest to those contemplating the use of this tool for research.

Development of a Pulverizer

In an attempt to obtain an insight into the mechanics of the breakage of coal, T. G. Calcott some time ago devised in our laboratories a small machine that could break large numbers of particles, under free crushing conditions, in such a way that none was broken more than once. By the use of this machine he was able, with S. R. Broadbent,* to make a considerable advance in the mathematical theory of coal breakage.

The principle of the machine is illustrated in Fig. 1. The cone rotates and spins the balls. A stream of particles is allowed to fall onto the point of the cone and slide down the curved surface. If a particle, in passing across the track of balls, is caught by one of them, the particle is broken and the fragments continue down the cone surface. In the early stages of the work, it was found that increasing the speed of rotation of the cone increased the efficiency of breakage of the particles. The efficiency was raised even further if vanes were added to the top of the cone. It was believed that the effect of both of these changes was to cause the particles, instead of sliding straight down the cone, to describe a spiral path with increased velocity. It was, then, less easy for a particle to cross the track of balls without being caught and broken.

In addition to the effect of rotational speed, there were a large number of factors that could be investigated. A considerable amount of work was carried out using a modified form of factorial experiment. The results, however, were disappointing because many anomalies were found and no simple explanation of the results seemed satisfactory. For example, the factorial experiment did not confirm the expected steady rise in efficiency with speed of rotation; sometimes the efficiency was increased, and sometimes it fell as the rotational speed increased.

It was at this time that we were able to borrow a 16mm WF3 Fastax camera and the services of an operator. The first photographs gave a clear explanation of the anomalies. As the speed of rotation of the cone was increased, the particles were first hurled more violently down the surface of the cone and along the track of the balls, as had been expected. Then at a critical speed they were thrown off the surface of the cone. As they did not then pass between the balls and a grinding surface, the breakage decreased considerably. At high speeds the particles were thrown even more violently off the cone, and passed over the top of the balls to be caught between the balls and the retaining ring, so that breakage again took place. With this explanation, the results of the factorial experiment began to fall into line. The whole operation of the machine was therefore reconsidered, and a new design was patented.

The method was so obviously useful that a complete equipment of the same type is now in continuous use in a variety of projects. However, in using photography, four main difficulties were found:

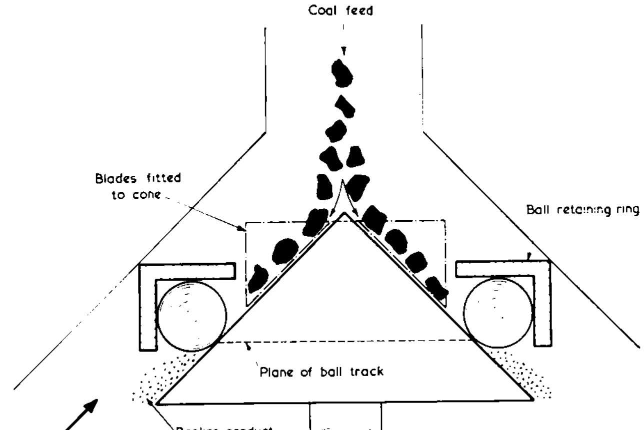

Fig. 1. Principles of pulverizer.

Presented on October 21, 1960, at the Fifth International Congress on High-Speed Photography in Washington, D.C., by Roland Jackson (who read the paper) and D. V. Simpson, British Coal Utilisation Research Assn., Leatherhead, Surrey, England.

* S. R. Broadbent and T. G. Calcott, "Coal breakage processes," *J. Inst. Fuel*, Dec., 1956, Jan., 1957; and *Phil. Trans. Roy. Soc.*, Ser. A., No. 960, Vol. 249, pp. 99–123, April 19, 1956.

(1) lighting,
(2) access to the point of current interest,
(3) interference with the quality of the films by the operation of the mill, and
(4) interpretation of the films.

Lighting

The material with which we are mainly concerned is coal. Since the metal surface of the machine soon becomes coated with a layer of coal dust, there is considerable difficulty in obtaining sufficient reflected light and the necessary contrast to enable us to produce films that show clearly what is happening. Satisfactory initial framing rates were of the order of 1000 frames/sec. As suitable lighting was not then available, we were driven to use an a-c arc lamp operating at 20 kw at a distance of about 7 ft from the object.

The intensity of light was sufficient to enable us to see the behavior of the coal and the balls; but the extinction of the arc each hundredth of a second caused a very irritating flicker on the screen when the film was played back at normal speed. We now find that four 750-w prefocused filament lamps placed within about one foot of the spot to be photographed give adequate exposure at the maximum framing rate and, of course, there is no flicker.

The lamps are sufficiently cheap to be regarded as expendable. Also, there is no problem in placing them so close to the pulverizer, because their front faces are shielded from flying particles by large watch glasses. The camera, however, is a different matter; it has to be protected not only from the possibility of damage by an occasional large flying particle, but also from the bad effect of clouds of dust. For this reason we now place it about 7 ft from the point of view, in a plastic bag, and use a 7-in. focal length, narrow-angle lens. However, this gives a depth of field of only 2 in. or so and a loss of perspective with consequent difficulties in interpretation. These are discussed later.

A considerable improvement in the pictures obtained has been effected by painting the inside surfaces of the pulverizer white, except the grinding zones. The increase in contrast is very marked and the white appearance is easily retained by cleaning the paint before each series of runs. The use of color film has since been found to ease considerably the difficulty of interpretation, but high-speed color film was not available at the time of these experiments.

The framing speeds we have found necessary are comparatively low, 1000 to 2000 frames/sec, and within the range of the Fastax camera. If we should require to go outside the range, we shall no doubt run into a new series of lighting problems.

Access

As will be seen from Fig. 1, the only way in which the mill can be easily photographed internally is along the surface of the cone in the direction of the arrow. In this view, the results of the grinding can be seen without great difficulty, but the movement of the particles from the apex of the cone to the ring is masked by the balls. For this reason we have been compelled to study the progress of the coal particles stage by stage through the pulverizer. The initial movement of coal dropping onto the cone and sliding down its surface was observed after removing the balls and ring. Although this technique enabled good photographs to be obtained, it was not completely satisfactory because removal of the ring and balls may have affected the initial motion of the particles before they reached the grinding zone. However, any such effect is likely to be of only secondary importance. Considerable advances have been made by studying first the motion of the particles down the cone itself, and then, after replacement of the elements, the appearance of the broken particles as they leave the ring of balls.

It would clearly be desirable to photograph the motion of the particles by viewing in a direction normal to the cone surface. However, we have been unable to accomplish this and have not seriously tried because there would be very great difficulty either in leaving a hole in the top cover or in using a self-cleaning window. For example, a stream of air passing over such a window to sweep it clean of dust would no doubt impose an over-riding effect upon the process that we wish to investigate. For convenience in changing the design of the pulverizer, the drive to the cone was modified so that the cone was suspended from (instead of being supported by) the driving shaft. Though installed for experimental purposes, this change of design has been of considerable value. By freeing all the space below the cone, it permits easy access for photography.

Interference

A major difficulty found in the investigation has been the presence of very fine dust which, of course, is a product of the process. The dust is inconvenient in that it can completely obscure the region of action we wish to photograph. It can be overcome to a considerable extent in four ways:

(1) by running the mill with small quantities of coal so that the production of dust is reduced,

(2) by applying suction near the point being studied to reduce even further the density of dust between the object and the camera,

(3) by timing the start of the film run to coincide with the initial flow of particles to the mill, and

(4) by silhouette photography.

These methods have so far proved successful, but they may have an effect upon the operation studied.

If the particles behave as individuals unaffected by either neighbors or by aerodynamic forces, the alterations introduced will have a negligible effect. When, however, we become interested in the extent of these interactions, the possible effects of the steps we have taken to assist our photography can no longer be ignored, and we shall have to seek other means. The first step, for example, obviously cannot be applied to the study of large throughputs of coal.

Interpretation

Difficulty has been found both in interpreting the photographs ourselves and in explaining the meaning to others. Because of the peculiar geometry of the setup it is not easy to visualize the motion of the particles when they are seen from an unusual angle.

Two directions of view have been preferred: (a) looking directly towards the apex of the cone and approximately parallel to the curved surface; and (b) looking approximately at right angles to this direction so that the ring and cone are seen in profile.

Shots in these two directions are fairly easy to understand, but a shot at about 45° to either of these cannot really be understood without reference to a model of the mill viewed in this direction. Nevertheless it can be valuable in obtaining data impossible to find in the other two positions.

As already noted, the use of a long focus lens leads to a general flattening of the picture, making the tracing of particle trajectories less accurate and more ambiguous. Some help can be obtained when particles are moving towards or away from the wall, by comparing the movement of a particle and its shadow. Trajectory tracing measurement of the projected image is also aided by using controlled frame by frame projection.

Other Applications of Photography

The example described has been selected because it shows the value of the technique and poses a number of special problems. High-speed photography is now being used in other branches of the research on pulverizers; but most of these applications, while of interest in the study of pulverizing, do not present any special photographic problems.

Examination of the behavior of elastic spheres moving over a plane surface with discontinuities has shown us the difficulty of obtaining a rolling motion with small spheres. It appears that they tend to move by bouncing. At much lower speeds, examination of the flow of spheres through orifices and in hoppers has been very illuminating.

The effect of the speed of application of a load upon the spread of stresses in a particle, is being studied photoelastically. In this case the framing speeds have been raised to the limit of the present camera, 8000 frames/sec, but no problem of lighting has arisen because of the easy experimental conditions. If higher speeds are needed to resolve the stress process, we shall need to enter a field that is at present completely new to us. To study breakage processes directly in coal will require even higher speeds, and we shall probably have to use some kind of spark sequence photography.

We can envisage special difficulties in doing this, however, because of the irregular rate at which the coal particles are broken. Regarded statistically, the breakage follows definable laws. However, synchronizing a series of a dozen or so pictures at microsecond intervals, with the random breakage of a particle within the field of view, is likely to prove more difficult.

Conclusions

(1) Our experience as beginners in this field has shown that the high-speed photographic technique is very powerful in leading to an understanding of the behavior of a machine such as the one described.

(2) Even when the machine is handling coal, which is not a very photogenic substance, it has been found comparatively easy to provide adequate lighting. Color film is also a great help in interpreting pictures that are normally low in contrast. Its slow speed, however, is a handicap.

(3) Simple alterations to the machine itself have been sufficient to permit a considerable degree of analysis of the motion of the machine and of the material being ground.

(4) A step-by-step examination of the machine, in which obscuring parts are removed and then replaced in turn, can permit useful information to be obtained even though it is impossible to see inside the machine when it operates in a normal manner.

(5) Interpretation of films taken from unusual angles may be geometrically difficult, and care must be taken to provide guidance for other viewers when the film is being explained.

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