Observations of Density Variations in Tobacco Rods by Neutron Radiography*

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SUMMARY

Neutron radiography was used to study the density of tobacco rods. Density variations in individual rods caused by local packing variations and the presence of more dense materials in the blend were easily discernible in both static and real-time radiographs. A density resolution of 0.35 mm was observed in the real-time system. By averaging center line density scans for several rods with the aid of an image processor, large scale variations in the density such as the increased packing at the rod ends could be measured. Comparison of the results from neutron radiography with those obtained by cutting rods into sections and weighing the sections showed good agreement. Both methods indicated the lighting end was approximately 9% more dense than the middle of the rod. This work has demonstrated that neutron radiography can be used to provide accurate density information about cigarette rods with considerably greater resolution and in much less time than sectioning and the commercial beta ray gauging technique.

ZUSAMMENFASSUNG

Unter Einsatz von Neutronenradiographie wurde die Dichte des Tabakstranges von Zigaretten untersucht. Schwankungen in der Dichte einzelner Tabakstränge, die auf lokal unterschiedliche Packungsdichte und auf

die Verwendung von Material höherer Füllfähigkeit in der Tabakmischung zurückzuführen sind, waren sowohl unter statischen Bedingungen wie auch unter Echtzeit-Bedingungen im Röntgenogramm deutlich erkennbar. Unter Echtzeit-Bedingungen war das Auflösungsvermögen 0,35 mm. Bei der Ermittlung von Durchschnittswerten für mehrere Tabakstränge unter Dichteabtastung entlang der Mittelachse mit Hilfe eines Bildprozeßrechners erwiesen sich starke Dichteschwankungen, wie sie die erhöhte Füllichte an den Strangenden mit sich bringt, als meßbar. Die Ergebnisse der Neutronenradiographie stimmten mit denen der Wägung von Strangsegmenten gut überein. Bei beiden Verfahren zeigte sich, daß die Tabakdichte am Brandende der Zigarette um ungefähr 9% höher ist als in der Mitte des Tabakstranges. Aus den vorliegenden Untersuchungen ergibt sich, daß sich die Neutronenradiographie zur genauen Ermittlung der Dichte in Tabaksträngen von Zigaretten eignet, wobei die Trennschärfe erheblich höher und der Zeitaufwand viel geringer ist als bei der Feststellung der Masse des Tabakstranges in einzelnen Abschnitten und bei der kommerziellen Betastrahlen-Meßtechnik.

RESUME

La densité des boudins de tabac a été étudiée au moyen de la neutronographie. Les variations de densité dans différents boudins de tabac qui sont imputables aux variations locales du bourrage ainsi qu'à la présence, dans le mélange de tabac, de matériaux ayant un pouvoir de remplissage plus élevé, ont été nettement mises en évidence sur les radiographies, tant dans des conditions

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Figure 1.
Mass attenuation coefficients of the elements for thermal neutrons and X-rays (from reference No. 6, used with permission).

Figure 2. Diagram of the beam port blockhouse showing shielding and locations of the shuttle and the neutron camera.

statiques qu'en temps réel. Un pouvoir de résolution de 0,35 mm a été observé en temps réel. Lors de la détermination de valeurs moyennes pour différents boudins de tabac, moyennant la détection de la densité le long de l'axe médian à l'aide d'un processeur graphique, il s'est avéré que les fortes variations de densité, telles que les provoque l'augmentation de la compacité aux extrémités du boudin, pouvaient être mesurées. Les résultats de la neutronographie sont en accord avec ceux obtenus par pesée de différents tronçons du boudin. Les deux procédés montrent que la densité de tabac à l'extrémité allumée de la cigarette est supérieure d'environ 9% à la densité au milieu du boudin. Il ressort de ces analyses que la neutronographie convient à la détermination précise de la densité dans les boudins de tabac de cigarettes, le pouvoir de résolution étant considérablement plus élevé et le temps investi de beaucoup inférieur à ce qu'il est lorsqu'on évalue la masse du boudin dans différents tronçons et qu'on recourt au procédé de mesure par rayons β mis en œuvre habituellement dans l'industrie.

INTRODUCTION

Relatively few studies have been published which deal with the structure and density of cigarette rods. Most of these studies have been concerned with the mechanism of burning in cigarettes but have used methods that provide information on structure and density. For example, EGERTON, GUGAN and WEINBERG published a paper in 1963 describing a variety of methods to examine the mechanism of smouldering in a cigarette (1). Specifically, X-rays were used to detect the melting of special metal alloy particles to determine temperature profiles in smouldering cigarettes. The packing density of the tobacco shreds could be seen in their radiographs although there was no apparent structural pattern. The X-rays did reveal an abrupt change in the density near the coal which the authors attributed to distillation and recondensation of the volatile components. Another method was the beta ray attenuation technique developed by JENKINS et al. to study the axial density changes in a burning cigarette (2). The authors were able to correlate the density changes occurring during smoking with the reported temperature profiles in the rod. They were also able to observe the buildup and re-evaporation of water and other condensables in the rod behind the coal. A conceptually similar device is used routinely to monitor the average rod density in high speed cigarette makers. In a study closely related to this work, GOLDRING, FIORE and GADZIALA used a number of methods to examine commercial and experimental tobacco rods (3). These methods included macrophotography of cigarettes after the paper had been removed, macrophotography of longitudinal serial cross sections and X-ray radiography. Of particular interest in relation to this work was the use of X-ray radiography to examine cigarette rods. While no structur-

al differences between commercial cigarettes were observed, variations in density of the packed tobacco were visible in the individual rods. X-ray radiography clearly showed the structure of experimental cigarette rods with unusual shred alignment made using long strands of reconstituted tobacco. Pieces of wire and stereo radiographs were employed to help visualize the three-dimensional structure of the rods. The X-ray technique was also useful in showing novel structures resulting from the use of low density tobacco materials.

This work reports the use of neutron radiography to study the density structure of cigarettes. The radiographic system was jointly developed by the personnel at the Philip Morris Research Center and the Department of Nuclear Engineering and Engineering Physics at the University of Virginia (4, 5). Neutron radiography is in many ways conceptually similar to X-ray radiography in that a beam of thermal neutrons (neutrons with energies of ~ 0.03 eV) can be used to make a two-dimensional projection of an object in much the same way X-rays are used for X-ray radiography. However, while X-ray attenuation is directly dependent on atomic number, thermal neutrons are efficiently attenuated by only a few specific elements as shown in Fig. 1 (6). This is because X-rays interact with the electron cloud of an element; the more electrons, the greater the interaction. Thermal neutrons, on the other hand, interact with the nucleus and this interaction is highly dependent on the nuclear structure of the atom. $^{10}\text{Boron}$ and gadolinium are good thermal neutron attenuators due to their large neutron capture cross sections whereas hydrogen is a good attenuator by virtue of its large neutron scattering cross section. Organic materials and water are clearly visible in neutron radiographs because of their hydrogen content while X-rays are generally more useful for imaging inorganic materials. In particular, neutron radiography is an excellent non-destructive method for investigating cigarette density structure.

EXPERIMENTAL

The real-time neutron radiography facility basically consists of two parts: the neutron beam and the neutron imaging system. The neutron beam is part of the University of Virginia 2 MW research reactor. One of the beam ports was modified to produce a neutron beam with a diameter of 15 cm and a neutron flux of 1×10^7 neutrons $\cdot \text{cm}^{-2} \cdot \text{s}^{-1}$. A blockhouse was constructed around the beam port to protect personnel from radiation when the neutron beam is in operation. A shuttle system was built so that objects could be moved in and out of the blockhouse during experiments without closing the beam (Fig. 2). The object to be radiographed is placed in the neutron beam on the shuttle table in front of a neutron imaging device. Two imaging devices are available for producing neutron radiographs: a real-time neutron camera and a

Figure 3.
Diagram of the Precise Optics neutron camera.

Figure 4.
Video image handling system for real-time neutron radiography.

gadolinium screen/film cassette that produces static neutron radiographs on photographic film. The real-time neutron camera is a video-based system produced by Precise Optics (Bayshore, N.Y.) (7, 8). A schematic diagram of the camera is shown in Fig. 3. The neutron image is produced in a 50 μm layer of gadolinium oxysulfide coated on the inside of the front screen of the camera. When the neutrons are absorbed by the gadolinium, electrons are released which cause the oxysulfide coating to scintillate. The photons from the scintillator screen are then amplified in an image intensifier tube. The output screen of the intensifier is viewed by a high resolution video camera. Thus, the original neutron images are converted to a video format which can be viewed on a TV monitor. This system produces high resolution neutron radiographs in real time, i.e. at the video frame rate of 30 frames/s. The neutron camera is mounted on a remotely controlled carrier which permits one to move or rotate the camera to optimize the image position. The position of the neutron camera in the blockhouse is shown in Fig. 2.

The video signal from the neutron camera is processed by the video imaging system shown in Fig. 4. The video signal first goes to a video tape recorder modified for high resolution black and white recording. This video tape recorder is used to replay the neutron images for review and analysis. A small, high resolution black and white video monitor is provided for viewing the live, unprocessed neutron images. The video signal next goes to a digital image processor, SAI Intellect 100 (Science Applications, Inc., San Diego, Calif.), for enhancement and analysis. The SAI Intellect 100 is a DEC 11/23 computer based system which digitizes the incoming analog video frames continuously into a matrix of 512×512 picture elements (pixels) each with an 8-bit (256) grey scale. Software functions of the image processor include recursive noise reduction, picture integration and differentiation, false colors, filtering masks for image enhancement, contrast enhancement and digital image storage. In addition, a number of specialized programs have been written including one to measure the density

of an object along a chosen line. Each of these functions has important applications in real-time radiography. For example, noise present from the random variations in the neutron flux can be reduced by the processor using either the recursive noise reduction function or picture integration although there is some loss of time resolution. The output of the image processor is viewed on a second monitor and can also be recorded on a second video tape recorder. The complete imaging system provides a powerful method for recording and analyzing the real-time neutron radiographs (5, 9).

Static neutron radiographs are made by placing the object to be radiographed in front of a light-proof cassette holding a gadolinium converter foil and X-ray film (6). The assembly is then placed in the neutron beam for approximately six minutes. The gadolinium foil absorbs the neutrons penetrating the object and releases radiation which exposes the film. The static radiographs have a higher resolution than the real-time radiographs due to the long exposure times and the fine grain of the film. The static method is, however, time consuming and cannot be used to follow motion or changes occurring over short time intervals. Static radiographs are used primarily to supplement the real-time system.

Density variations in the tobacco rods of experimental 85 mm filtered cigarettes were determined by neutron radiography and sectioning. The cigarettes were made on a maker designed to pack slightly more tobacco at both ends of the rod. A line density program for the image processor was written to calculate the relative densities in a cigarette rod from the pixel luminance

(brightness) values along either a horizontal or vertical line. The program stores the video image of the object in a digital matrix of 512×512 pixels. The operator then chooses the line for analysis with a movable cursor. The program can display or print the pixel luminances along the chosen line or it can calculate the relative density for each pixel if the background data for the line was previously stored. The relative density of the tobacco rod is calculated, in effect, from Beer's law on a pixel by pixel basis:

$$\text{relative density (n)} = -\ln [I(n) / I_0(n)] \quad , \quad [1]$$

where $I(n)$ and $I_0(n)$ are the pixel luminances of the n th pixel in the video line with and without the tobacco rod. The use of Beer's law to calculate a relative density assumes that the object thickness and composition are constant along the scanned line. The thickness of the cigarette rod at the center line was uniformly 8 mm. The average composition of the rod can also be safely assumed to be constant since the overall carbon and hydrogen content of the tobacco does not vary to any appreciable extent. Hydrogen and, to a lesser degree, carbon are the only two elements present naturally in tobacco in large enough quantities to be of use in neutron radiography. Thus, the relative density calculated from the radiographic data is directly related to the true density of the tobacco rod. The luminance data for the cigarettes were acquired from stored video images having a 3-bit noise reduction to reduce the amount of random noise present in the real-time radiographs. The relative densities were calculated for the center line of each cigarette, except for the first cigarette where all lines through the cigarette were examined. The cigarettes were examined separately and in the same position so that the background data for each cigarette were the same.

Rod densities were also measured by sectioning and weighing the first 54 mm of tobacco rods from a second set of cigarettes from the same maker run. Five groups of 10 cigarettes were cut into 10 sections as shown in Fig. 5. Reported weights are for 10 sections from the same position in the rod averaged for the five groups. The sectioning and weighing were carried out in a controlled environment room with a relative humidity of 60% and a temperature of 22 °C.

RESULTS AND DISCUSSION

The average weight per 10 sections is plotted against the section position in Fig. 5 with the error bars indicating the standard deviations in the weights of the five groups of ten sections each. Figure 5 shows that the lighting end of the rod is more dense than the middle sections by approximately 9%. The filter end of the tobacco rod was not sectioned, thus it is not possible to ascertain whether the density is also greater at this end.

Figure 5.

Average weight of ten sections as a function of sectional position. The section positions are shown in the upper portion of the figure. Error bars represent the standard deviations in the weights of the five groups of ten sections for each position.

A static radiograph of four of the experimental cigarettes is shown in Fig. 6. Although each individual shred is not visible, one can discern some of the more dense pieces of tobacco as well as the density variations in the tobacco bed. Figure 7 presents the pixel luminances along the center line of cigarette No. 1 and the background luminances for the same line. The background luminance values show that the neutron flux across the beam is not constant but is slightly greater in the center of the beam. High luminance values indicate areas of low density while low values correspond to

Figure 6.

Static radiograph of four cigarettes from the sectioning experiments.

Figure 7.

Pixel luminance data for the center line of a cigarette and the background luminance data for the same line. The filter region of the cigarette is on the right-hand side of the figure. Each pixel represents 0.35 mm of the 85 mm rod length.

Figure 8.

Relative density for the center line of a cigarette calculated from the luminance data in Fig. 7. The filter region is the area of lower density on the right-hand side of the figure.

Figure 9.

Relative density from the average of all horizontal lines in the image of a single cigarette.

Figure 10.

Average relative density calculated from the center line data of ten experimental cigarettes.

areas of high density. While Fig. 7 gives some indication of the density along the center line of the cigarette, it is necessary to use Beer's law to obtain a true measure of the relative density. The pixel by pixel calculation of the relative density also corrected for the variation in the neutron flux across the beam. The relative density along the center line of cigarette No. 1 is presented in Fig. 8. Each pixel represents 0.35 mm of rod length and 0.44 mm of rod width. On this distance scale large variations in the rod density are easily apparent. Some of the small variations are due to the statistical noise present in the real-time radiographs. This noise is most clearly visible in the filter portion of the cigarette since the filter density is more uniform. It is difficult to observe the effect of dense ends in the density measurements made from a single line scan of an individual cigarette because the effect is partially masked by the density variations due to other mechanisms such as random variations in the rod density and pieces of more dense material. One way to overcome this problem is to average the density scans over all the lines in the radiographic image of the cigarette as shown in Fig. 9. In this case, the ends of the tobacco rod definitely appear more dense than the middle of the rod. Another way to treat the data is to average the center line density scans from all ten cigarettes (Fig. 10). The dense ends are even more apparent in this figure. To simplify comparing the data in Fig. 10 with those in Fig. 5, the pixel distance scale was divided into 5.4 mm sections and the relative density values for the pixels in each section were averaged. A linear regression was used to convert the average relative density values to weights (equation 2):

$$\text{weight}/10 \text{ sections} = 0.3265 \cdot \text{ARD}^* + 0.394. \quad [2]$$

The correlation coefficient was 0.944. The original weight data and the converted values from neutron ra-

* ARD = average relative density.

Figure 11.

Comparison of the sectioning data from Fig. 5 with the relative density data from Fig. 10. The pixel scale in Fig. 10 has been converted to the section scale based on a 5.4 mm section length and a pixel width of 0.35 mm. A linear regression (equation 2) was used to convert the relative density averages for each section to weights.

diography are plotted against section number in Fig. 11. The agreement between the two methods is good. The first section value from radiography is somewhat low probably due to the loss of some of the tobacco from the lighting end of a few cigarettes during handling.

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