CHANGE IN GAS VOLUME DURING PUFFING OF A LIT CIGARETTE

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INTRODUCTION

A knowledge of the relationship between the volume of air entering a lit cigarette during puffing and the volume of smoke produced is helpful in understanding the mechanism of burning of cigarettes. In addition, it is essential to have this knowledge to properly conduct smoking experiments, especially those using "reverse smoking," in which a certain amount of air is forced through the lit cigarette using a positive pressure to produce smoke for further study. The volume balance of combustion can be used also in analyzing and checking the reported gas composition of smoke.

There have been two or three attempts in the past to determine the volume change during puffing, but the reported results are not in agreement with each other.

For example, while Schur and Rickards (1) reported in 1957 that there is a significant volume change during puffing of cigarettes, Mitchell (2) reported in 1962 that there is no volume change and Newsome and Keith (3) reported in 1957 that there is some volume change which is about half of that reported by Schur and Rickards. It is also possible to deduce the existence of such a volume change from the reported gas composition of smoke (3-8). For example, the proportion by volume of nitrogen in smoke is reported by Keith and Tesh (4) to be 67.2%. The corresponding value for nitrogen in dry air is 78%. Assuming that only negligible amounts of nitrogen are consumed by combustion reactions, this indicates at least a 16% increase in the total volume due to combustion. There has been no attempt heretofore to study how this volume change depends on time during a puff or how it varies with experimental procedures.

The purpose of the work reported here was to ascertain whether there is actually any volume change and also to obtain, using fast-responding and sensitive instruments, the instantaneous volume changes during the

Figure 1—Apparatus for determining volume change during combustion of cigarettes.
puffing. These volume changes were determined by measuring the flow rate of the air entering the cigarette while smoke is produced at a known constant rate. By determining the volume change as a function of a time, it was possible to get some insight into the progress of burning during puffing.

EXPERIMENTAL

The experiments consisted essentially of mechanical puffing of a lit cigarette at 16.57 cc/sec rate for two seconds and measuring the flow rate of air entering the cigarette. The apparatus used (Fig. 1) consists of two major parts, one for puffing and the other for measuring the flow rate of incoming air.

The part for mechanical puffing consists of a cigarette holder connected to a vacuum line through a limiting orifice and solenoid valve operated by a pair of electrical timers. Timer 1 activated timer 2 once every minute or when desired. One of the cams of timer 2 was adjusted to energize the solenoid, and thereby to open the valve between the vacuum line and the limiting orifice, for two seconds. Adjustments of the two produced the puff for two seconds at desired times.

A Cambridge filter held in a filter holder between the cigarette and the limiting orifice prevented the deposition of particulate matter in the orifice. The orifice used in the present experiments maintained a flow rate of 16.57 cc/sec.

Experiments were conducted with 100 mm cigarettes burning between 1 and 4 cm from the front. The cigarette was encased within a glass jacket fitting a ground glass joint on the cigarette holder. The air flow into the jacket was determined by measuring the pressure drop across a 2.6 cm long regular cigarette filter. At the resistance used, the pressure drop was less than 8 cm H₂O. This is less than 1% of atmospheric pressure (1033.2 cm) so that the expansion of the entering air in passing through the flow meter can be neglected.

A ±1 psi pressure transducer with a natural frequency of about 2000 cps under our conditions was used to measure the pressure drop. Its negative probe was introduced between the cigarette filter and the jacket and the positive probe was exposed to the atmosphere.

Any flow through the flow meter produces a corresponding electrical signal from the transducer. This AC signal is demodulated by a transducer demodulator and the output from the latter is fed into a strip chart recorder and an oscilloscope fitted with a camera. The oscilloscope and the camera shutter were both triggered a fraction of a second before the beginning of a puff by timer 2. The arrangement placed the beginning of the puff at the same point on all photographs of the oscilloscope traces. The oscilloscope deflection was directly proportional to the flow rate of air.

With an unlit cigarette in the holder, the flow rate into the glass jacket is essentially the same as the flow rate of gas through the resistance. Information on volume change due to burning can be obtained by comparing oscilloscope traces obtained with the lit and unlit cigarettes. Volumes were obtained as integrals of flow rates by weighing xerography copies of the relevant sections. Weighing of seven different xerography copies of a particular area gave a mean reading of 0.2618 ± 0.0045 cm³.

For calculating the volume change during combustion, the ratio between the areas of two regions was used. The standard deviation for a volume change of 14.7% for a particular test, as obtained from 8 different measurements (xerography and weighing) of a single photograph was found to be 0.4%. For larger volume changes the standard deviation in a single measurement of the volume change than that in the above case.

Smoke filtrate has somewhat different physical properties than air and the flow through a limiting orifice may be affected by these. This problem was studied with the help of the experimental set up shown schematically in Fig. 2. The part for producing the standard puff is the same as that described earlier. The flow rate through the system was measured by means of a pressure transducer, a soap bubble meter, and a rotameter with lit and unlit cigarettes in the holder. Only one of these three instruments was used during any particular experiment. Their positions are shown in Fig. 2.

With the unlit cigarette in the holder, air flows through the system, including the limiting orifice, whereas with the lit cigarette in the holder, smoke flows through it. As mentioned in footnote 3, a regular cigarette filter cannot be used as a flow meter when it is to be between the cigarette and the limiting orifice. A glass tube (3 mm dia x 4.4 cm length) was used as the resistance element in this case. The length of the tube has to be limited to keep the dead volume low, with the result that the pressure drop is significantly less than that obtained with the filter. Therefore, a more sensitive ±0.1 psi transducer was used in this experiment. The span of the indicator was adjusted to 2.5 cm of water full scale.

During preliminary tests, it was observed that the time interval between the enclosing of a lit cigarette with the jacket and the beginning of the puff is an important parameter influencing the volume change during puffing. This time interval was controlled and measured by noting the distance between the strip chart recordings of pressure changes due to these events. During the above time interval, the glow cone is essentially being choked as there is no supply of additional oxygen to the glow cone. This time period is therefore called in this paper "choking duration."

Because a sensitive and quickly responding transducer-demodulator-oscilloscope combination was used, it was possible to obtain rapid and accurate information in the flow rates of the entering air in a function of time during the two-second puffs. The jacket used was sufficiently small to have only an insignificant effect on the sensitivity of the flow rate measured. On the other hand, any expansion of air inside the jacket due to heat from the glow cone and the amount of side-
The stream that might re-enter the cigarette during puffing is increased by the use of a smaller jacket.

RESULTS AND DISCUSSION

Effect of Smoke on Flow Rate Control by the Limiting Orifice. Measurements to determine the effect of smoke on flow rate control by a limiting orifice gave the following results:

(a) Tests with bubble meter—Data obtained with this technique was accurate only within 2%. With an unlit cigarette in the holder and, therefore, air flowing through the system, the volume found to be 32.6. With a lit cigarette in the holder and, therefore, smoke flowing through the system, it was 32.7. It can be seen that smoke has no effect on the flow rate control by the limiting orifice within the experimental error of this method.

(b) Tests with rotameter for gas flow—The rotameter gave a reading of 20.3 ± 0.04. The corresponding reading for smoke was 20.0 ± 0.05. The difference could be due to either an actual decrease in the flow rate or a decrease in the density of the gas medium. The nonparticulate portion of the smoke contains, however, more carbon dioxide and less oxygen and nitrogen than is present in air and, therefore, has a higher density. These tests can therefore be taken to indicate a reduction in flow rate when the gas flowing through the system is smoke instead of air. The percentage reduction is somewhat more than 1.5%.

(c) Tests with the transducer—The flow rate was found to be approximately 2% less with the smoke flowing through the system instead of air. Two typical oscillograph traces obtained for the air and smoke flow are shown in Figs. 3a and 3b, respectively.

The above results indicate that there is a minor effect between 4% (bubble method) and 1.5% (rotameter) of smoke on flow rate control by limiting orifice. It is possible that the bubble meter technique did not show such an effect because of the larger experimental error associated with it. Also, since a transducer set was used for determining the volume change during puffing, a 2% correction which seemed a reasonable estimate was therefore applied.

Volume Change due to Burning. A typical trace for the air flow into an unlit cigarette is shown in Fig. 4. The dashed line represents approximately the corresponding curve that would be obtained if the gas flowing were smoke instead of air. It is with this dashed line that comparisons of traces obtained with lit cigarettes are normally made. An example of the trace obtained with a lit cigarette in the holder and with negligible choking of the glow cone is shown in Fig. 5. For the purpose of comparison, the dashed line of Fig. 4 is superimposed on Fig. 5. It can be seen that for the first one-fifth or so of a second, the flow rate of air entering the cigarette is higher than that of the smoke exiting from the cigarette (stage 1) and in the remaining time of the two-second puff (stage 2) it is lower than that of the smoke. It can also be seen that there is a gas flow from the chamber to the outside for about one-third of a second after the completion of the puff (stage 3). The instantaneous volume change due to burning (the difference between the solid line and the dashed line) in terms of percentage of the puffing rate is given in Fig. 6 as a function of time.

The above results show that in the beginning of the puff the volume of gas consumed by the burning of the cigarette is larger than that produced by the burning. Then, as the burning proceeds, more is produced than consumed. The observed change in flow rate during the puff is in qualitative agreement with

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Figure 3a & b—Pressure drop versus time for two-second puffs with (a) unlit and (b) lit cigarettes in the cigarette holder and transducer probes between cigarette and limiting orifice. X-axis 1 division = 0.225 sec.; y-axis 1 division = 3.06 cc/sec. at atmospheric pressure.

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Figure 4—Profile of air entering an unlit cigarette during a two-second puff. Dotted line indicates the approximate profile that would have been obtained if smoke was used instead of air. X-axis 1 division = 0.225 sec.; y-axis 1 division = 4.13 cc/sec. at atmospheric pressure.

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The results of Jarrell and de la Burde (6) which indicate that the oxygen consumed by the burning reactions increases as the burning proceeds with a simultaneous increase in the carbon monoxide and carbon dioxide content of the smoke. The increase of volume change in the beginning of puffing is considered at present to be at least partly due to a change in burning characteristics.

Temperature changes within the jacket will cause
some flow of air through the flow meter and thus simulate volume changes due to puffing. (It is sufficient to raise the temperature of about 5 cc of the air inside the jacket — 25% of its volume — through 108 to obtain the increase in volume observed during stage 3.) In particular, a heating of the still air at the end of the puff could cause an outflow as observed during stage 3, and cooling by inflow of cold air could give rise to the increased inflow observed in stage 1. However, observation of the outflow recorded immediately after closing of the jacket at the beginning of each experiment indicates that the actual volume change due to heating of the air in the jacket is small compared to the observed effects. Presumably, the cooling effect of the jacket wall predominates.

Preliminary experiments showed that there were no noticeable differences between puffs in which the position of the glow cone varied between 1 and 3 cm from the front end. This was also an experimentally convenient range and was used in all experiments.

Volume changes during the different stages of puffing of a lit cigarette are given in Table 1. The choking durations are also given in Table 1.

The first nine tests are those that were done with the least experimentally possible choking durations. In tests 10–21, choking duration was purposely varied. Choking for durations longer than that reported often produced extinction of the glow cone. The above results are plotted in Figs. 7 and 8.

During the two-second puff and with negligible choking, the mean volume change is 23 ± 4% of the air entering the cigarette. Since the wrapping paper is porous, only a part of the air that entered the cigarette has actually gone through the glow cone and, therefore, the volume increase due to burning is more than 23% of the air that has come in contact with the glow cone. The total mean volume change during the puffing and the immediately following stage 3 is 29 ± 4% of the air entering the cigarette.

As mentioned earlier, the reported composition of cigarette smoke indicates an increase in volume due to burning and this is in qualitative agreement with the present results. If no nitrogen has been consumed or produced by the burning, the 23 ± 4% increase in volume should correspond to a nitrogen content of 63.4 ± 2% (by volume) in the smoke leaving the cigarette. The above value is somewhat lower than the value (67%) reported by Keith and Tesh for the nitrogen content in smoke. It is also lower than the 73–75% by volume observed from the data of Makhlachev (9) and the 66% from the data of Phillips (5). These higher values obtained by direct analysis of smoke could be partly due to production, if any, of nitrogen during burning and partly due to diffusion of nitrogen.

Table 1. Volume change by combustion at various stages

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Figure 6—Instantaneous volume change due to burning of a cigarette as percentage of puff flow rate.
into the smoke through the wrapping paper (10, 11). In this connection with the former possibility, it might be noted that Jarrell and de la Burde (6) found no nitrogen in the mainstream smoke of cigarettes burned in a nitrogen-free atmosphere, indicating that nitrogen is not produced by the pyrolysis reactions.

The nitrogen to argon ratio evaluated from the data of Laurene, Young and Greene (8) is 77-84 for smoke and 88 for air. Assuming that argon is neither consumed or produced, this indicates that some of the nitrogen of the air is consumed during burning. On the other hand, it is also possible that the above difference in nitrogen to argon ratio is due to experimental error. The nitrogen to argon ratio that could be obtained from the data of Keith and Tesh is 84 for smoke which can be compared with a value of 83.6 given for air in the literature (12).

The scattering of values for the volume change, for choking times of less than five seconds, might be due to a variation in cigarette properties—such as tobacco packing and wrapping paper porosity—that govern the burning of the cigarette. Any variation in volume change due to a variation in cigarette butt length or puff number might also contribute to the scatter. The amount of air that leaks through the wrapping paper decreases as the butt length decreases and, therefore, the amount of air that goes through the glow cone may increase significantly when the burning region is nearer to the mouth tip.

With regard to the reverse smoking technique, the above results show that due to the variation in change in flow rate during a puff as well as due to considerable differences in behavior between individual cigarettes, it will be very difficult to control the air input into the cigarette so as to get a constant or predetermined puff flow rate or even a predetermined total smoke volume.

It can be seen from Figs. 7 and 8 that the volume change due to burning decreases significantly if the glow cone is choked. A typical oscilloscope tracing obtained during pulling of a lit cigarette after some amount of choking is given in Fig. 9 and may be compared with that of Fig. 5 obtained with no choking. In the present experimental set up the effect of choking could be noticed if the choking duration were more than about 5 seconds. This time interval would be larger or smaller than the one reported here if the jacket used for enclosing the cigarette is larger or smaller than the one used here (2 cm dia x 6.3 cm length), because the amount of oxygen available for normal smoldering of the cigarette depends upon the volume of the jacket. Experiments with a larger jacket confirmed this expectation. A significant increase in the size of the jacket increases, however, the dead volume between the probes and the solenoid valve and reduces the sensitivity of the method. An examination of the diagram of the jacket used by Mitchell (2) suggests that significant choking of the glow cone might have occurred in his system. This could be the reason for his observation in 1962 that the volume change due to burning was zero.

SUMMARY

A knowledge of the change of gas volume during pulling is important for the analysis of the burning process of cigarettes and is required in the correlation of reverse smoking experiments (in which a positive pressure is used to force air through a cigarette) with conventional ones in which smoke is sucked from it. A sensitive and rapidly responding pressure transducer-oscilloscope combination was used to measure the rate at which air was entering the cigarette while smoke was sucked for two seconds at a constant rate.
of 16.57 cc/sec. The volume change was an increase averaging 23% of the volume of entering air. During the first fraction of a second, there was a small decrease in the volume change followed by a steady increase. After completion of a second puff, the cigarette continued to produce gases for about one third of a second, making the total volume change about 29%. If the supply of air to the glow cone is reduced prior to the puff, the volume increase is reduced. Literature reports that the volume change is zero might be due to such choking of the cigarette for a few seconds prior to the puff.

ACKNOWLEDGEMENT

The author wishes to thank Dr. K. J. Myself for several enlightening discussions during the course of this work.

LITERATURE CITED

8. Laurene, A. H., G. W. Young and G. H. Greene, unpublished work at the R. J. Reynolds Research Laboratory.