Ⅱ. 特別講演 要旨

EFFECT OF CIGARETTE PAPER ON CIGARETTEAPPEARANCE, BURN RATE AND SIDESTREAM SMOKE

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Summary

The smoke from a burning cigarette is classified as mainstream, which is the smoke inhaled by the smoker during a puff, and sidestream, which is defined by ISO 10185 as all smoke which leaves a cigarette during the smoking process other than from the butt end. Most of the sidestream smoke is generated during static burn, that is, in between puffs. The amount of sidestream smoke generated by a cigarette depends on the cigarette construction, tobacco blend, and properties of the cigarette paper. The main paper properties affecting sidestream smoke generation are: porosity, basis weight, type and amount of filler, type and amount of burn additive.

Sidestream smoke is composed of a visible phase (small liquid droplets) and an invisible phase (gaseous molecules). This paper focuses on the visible portion of the sidestream smoke. Optical methods, which are based on the relationship between light scattering and density of the rising plume of smoke, have been used successfully by the industry. However, the present trend is to use gravimetric methods where the particulate matter is captured on a Cambridge® filter pad and weighed. The gaseous

portion of the sidestream smoke, which does not contribute to the visible sidestream smoke, passes through the Cambridge filter pad.

Sidestream smoke reduction is achieved by modifying certain mass transport processes occurring in a smoldering cigarette. There are four main pathways for reducing sidestream smoke: A) less tobacco burned, B) slower rate of tobacco combustion, C) more efficient trapping of smoke by the cigarette paper, and D) more complete combustion of tobacco. This paper discusses how the physical properties of paper and cigarette construction affect sidestream smoke reduction via the above four mechanisms.

Sidestream Smoke Formation

In a smoldering cigarette the hot coal and its accompanying inorganic ash advance gradually toward the filter end of the cigarette. Because of the high temperature of the coal, about 900 ℃, the visible smoke entering the coal region is burned to completion and no visible smoke exits the coal region. However, in the intermediate region between the advancing coal and the more distant parts of the unburned cigarette, various destructive distillation and partial combustion processes occur. Externally this region appears as a black char line, which comprises the incompletely burnt cellulose portion of the cigarette paper along with the original inorganic mineral fillers. The char line becomes orders of magnitude more permeable than the original cigarette paper once the cellulose fibers begin to thermally decompose. The high permeability of the char line permits easy egress of the sidestream smoke as evidenced by the rising plume of smoke rising from this region of a smoldering cigarette.

Sidestream smoke is actually a fog, i.e., a suspension of small liquid droplets in a gas phase. This fog forms when high boiling point compounds generated during the destructive distillation of the tobacco supercool and spontaneously nucleate to form a new liquid phase in the form of myriad of small liquid droplets. Once formed, this fog is very stable and can be depleted of its liquid droplet content only by highly efficient filtration, which is not available at the char line.

Interaction between Sidestream Smoke and Static Burn Rate

The amount of sidestream smoke generated can be considered on a total basis per cigarette (mg/cigarette) or on a rate basis (mg/min). The bridge between these two considerations is the static burn rate. The rate of sidestream smoke generation (mg/min) = total sidestream smoke (mg/cig.) x static burn rate (mm/min) / length of cigarette smoked (mm/cig.). (An alternative is to divide the total sidestream smoke by the puff number in order to obtain a rate expression.)

Considering sidestream smoke on a rate basis is more appropriate since that is what the smoker sees as he/she is smoking the cigarette. In order to obtain the total amount of sidestream smoke, the smoker would have to mentally integrate the rate of sidestream smoke generation over the length of the cigarette.

Based on the above equation it is possible, for example, to decrease the total amount of sidestream smoke, yet increase the rate of sidestream smoke generation because the static burn rate has increased!

Mechanism of Sidestream Smoke Reduction

There are four main mechanisms for reducing sidestream smoke: A) less tobacco burned, B) slower rate of tobacco combustion, C) more efficient trapping of smoke, and D) more complete combustion.

The trapping and more complete combustion mechanisms work in tandem. First, the smoke must be prevented from escaping through the cigarette as much as possible by having the paper, char and ash form a shroud around the smoldering tobacco, which retards the escape of the vapors. Second, increasing the exposure of the vapors to the hot coal results in more complete combustion and therefore a lower average molecular weight of the smoke. (As the molecular weight decreases, the visibility of the smoke in ambient conditions also decreases.) Incorporating within the paper structure condensing sites for the vapors helps to achieve more complete combustion.

At a first glance, this condensing mechanism would seem to offer only a temporary and inconsequential relief from visible sidestream smoke generation. The ever-advancing coal soon reboils these condensed liquids. However, now the reboiling takes place on the outer periphery of the cigarette where the ambient environment (air) is much richer in oxygen than the interior of the cigarette where the vapors were first generated. Due to the enhanced oxygen content, the vapors are more efficiently combusted to yield gaseous products of lower molecular weight (lower boiling point) which cannot nucleate to form visible smoke at normal ambient temperatures.

A) Less Tobacco Burned

The tobacco in a cigarette constitutes almost all of the fuel for combustion. Obviously, as the amount of tobacco is reduced so is the sidestream smoke generation. Therefore, using expanded tobacco, reducing cigarette diameter and reducing tobacco-packing density all result in lower levels of total sidestream smoke.

B) Slower Rate of Tobacco Combustion

The rate of sidestream smoke generation can by reduced by slowing down the burn rate of tobacco. This can be accomplished, for example, by using slower burning tobaccos, incorporating burn-retarding additives in the tobacco blend, or increasing packing density.

Cigarette paper porosity controls the transport of oxygen from the surroundings to the combustion zone. As the paper porosity decreases, the influx of oxygen decreases, and hence the rate of sidestream smoke generation also decreases. An extreme example is a PAPIROSSI cigarette, which generates little sidestream smoke, because the paper porosity is near zero.

C) More Efficient Trapping of Sidestream Smoke

As paper porosity decreases, it is more difficult for the smoke to exit through the incompletely burnt paper, i.e., the paper becomes more efficient at trapping smoke.

As the basis weight increases, the paper becomes more effective at preventing smoke from escaping. (Basis weight of paper is usually defined as the weight in grams of one square meter of paper.) Also, the number of available condensing sites increases. Both effects result in lower sidestream smoke generation on a total or rate basis. As the basis weight of paper increases, the static burn rate increases. However, the increase in burn rate is more than offset by the more efficient trapping of smoke and the presence of a larger number of condensing sites, and therefore, the rate of sidestream smoke generation usually decreases with increasing basis weight.

In order for cigarette paper to be effective at reducing sidestream smoke, it must also contain a sintering agent to generate a coherent and continuous ash, which retards the escape of smoke. Sintering occurs when a high enough temperature is reached where individual particles adhere to each other. Carboxylic acid salts function by lightly sintering the charred paper and the inorganic ash. If these salts are not present, the char and the ash structure are full of large cracks or fissures. Since the vapors in the interior of a cigarette are under an appreciable positive pressure, the vapors will preferentially escape through the path of least resistance, i.e., through the fissures, thereby completely bypassing the condensing filler surfaces. However, once the benefit obtained from the elimination of fissures is obtained, additional amounts of the carboxylic acid salt will only result in loss of condensing sites due to excessive sintering of the filler particles.

Salts, such as carboxylic acid, also affect static burn rate. Generally, as the amount of salt increases, the static burn rate initially increases, and then decreases. Therefore, the effect of salt on the rate of sidestream smoke generation is the sum of all of the preceding effects and can lead to a very complex set of interactions. At low salt levels, the benefits of ash sintering usually outweigh the other effects, and therefore, the rate of sidestream smoke generation decreases with increasing amounts of salt.

D) More Complete Combustion

As the surface area of the filler in the paper increases, the area available for condensation increases and therefore, the total sidestream smoke generation decreases. The contribution of the cellulose fiber portion to the total surface area available for condensation is small compared to the contribution of the inorganic filler. The total available surface area depends on the specific surface area of the filler (square meters per gram of filler, m2/g), weight fraction of the filler in the paper, and the basis weight of the paper. In other words, the surface area of the filler in the paper can be increased by using a filler with a higher specific surface area, and/or increasing the percentage of filler in the paper, and/or increasing the basis weight of paper. The generation of visible sidestream smoke initially decreases rapidly as the surface area of the filler in the paper increases. The generation of sidestream smoke gradually levels off as the condensation of vapors on the filler surface becomes less and less rate limiting in its influence on visible sidestream smoke generation.

The desired large superficial surface area of the filler must not decrease significantly during heating of the filler as the hot coal approaches. Some fillers, which have a large surface area at room temperature, lose surface area upon heating due to melting, fusing or collapse of the filler structure. For example, certain silica hydrogels lose over 90% of their surface area when heated to 400 ℃.

Not all thermally unstable fillers lose surface area upon heating. When heated, some solids form new crystalline phases which differ in density. The resulting phase transformation is accompanied by crystal shattering and the formation of new surfaces. One of the best examples of a filler whose surface area actually increases upon heating is magnesium hydroxide which rapidly decomposes at about 350℃ to magnesium oxide. The freshly formed magnesium oxide has several times greater surface area than the magnesium hydroxide which was originally present in the paper. This several-fold increase in surface area helps to explain why cigarette papers containing magnesium hydroxide are effective in reducing sidestream smoke.

However, as the total filler surface area in the paper increases, the static burn rate also increases. The impact on the rate of sidestream smoke generation depends on whether the static burn rate is increasing faster or the total sidestream smoke generation is decreasing faster.

Figures 1 and 2 show schematically the complex effects of porosity, basis weight, salt level and filler surface area on the total and rate of sidestream smoke generation, respectively. These graphs depict general trends. The actual levels of sidestream smoke depend on the physical properties of the paper, its composition as well as cigarette properties.

Figure 1: Effect of paper properties on the total sidestream smoke generation

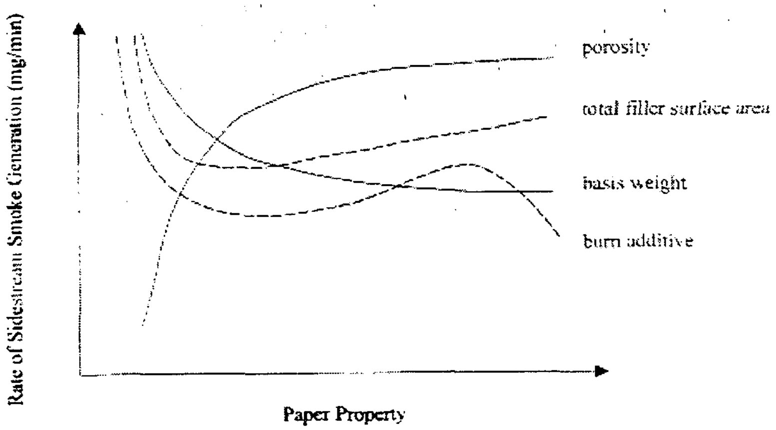
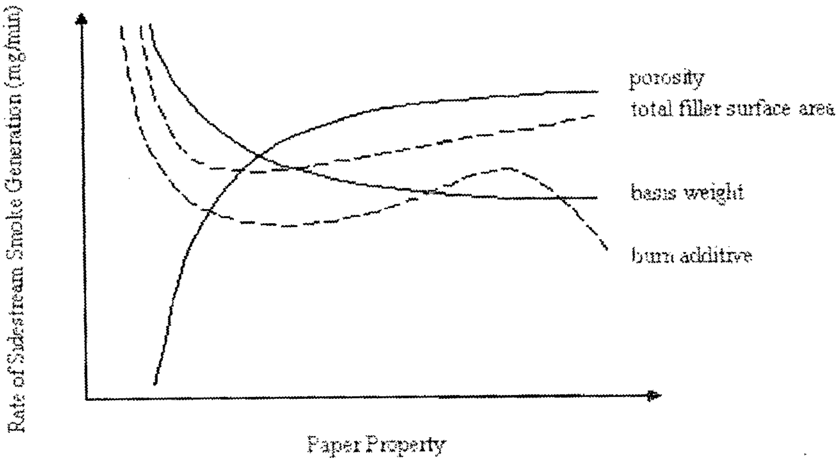


Figure 2: Effect of paper properties on the rate of sidestream smoke generation



OTHER CONSIDERATIONS

The use of double-wrap instead of a single-wrap construction offers additional flexibility in sidestream smoke reduction mainly by achieving more efficient trapping of smoke and slowing down the tobacco combustion. Equipment for making double-wrapped cigarettes is available and can be adapted to most cigarette makers.

Perforating cigarette paper creates holes in the unburned portion of the paper, which can be large enough to allow easy egress of the smoke. In this respect, perforation increases sidestream smoke generation. Perforating cigarette paper has a negligible effect on the static burn rate, but it does make the puffs less efficient and therefore it increases the puff count. The net result is that it takes longer for the cigarette to be smoked and therefore the total amount of sidestream smoke increases.

BALANCE OF PROPERTIES

In the foregoing discussion, the focus was on paper and cigarette properties necessary to minimize sidestream smoke generation. However, cigarette paper mu meet many requirements in order for the cigarette to be a viable product. These requirements often conflict with each other. For example, while reducing paper porosity is helpful in reducing sidestream smoke, it is generally perceived as causing worsening of taste and staining. Therefore, the final cigarette and cigarette paper designs represent a compromise among the many important properties. The cigarette and cigarette paper designers must consider all factors carefully and create a balance while emphasizing the desired features, such as, sidestream smoke reduction.

Tables 1 and 2 show the various interactions of properties for cigarette paper and cigarette parameters. The usual effects are shown. Exceptions can and do occur. Tables show the effect on cigarette performance as the paper property or cigarette property ***increases***. (The first arrow indicates the usual initial effect as the property increases, while the second arrow indicates the subsequent effect.)

Table 1:	Porosity	Basis Weight	Surface Area of Filler	Amount of Filler	Salt Amount
Mechanism1	B, C	C, D	D	D	C, D
SS Total (mg/cig)	↑	↓	↓	↓	↓ ↑
SS Rate (mg/min)	↑	↓	↓ ↑	↑	↓ ↑
SBR2 (mm/min)	↑	↑	↑	↑	↓ ↑
Puff Count	↓	↓	↓	↓	↓ ↑
TPM3 (mg/cig)	↑	↓	↓	↓	↓ ↑
Ash Appearance	↔	↑	↑	↑	↓ ↑
Taste	↑	↓	↔	↔	↓

Table 2:	Paper Perforation	Cigarette Length	Cigarette Diameter	Tobacco Density
Mechanism1	C		A	A, B
SS Total (mg/cig)	↑	↑	↑	↑
SS Rate (mg/min)	↑	↔	↑	↑
SBR2 (mm/min)	↔	↔	↓	↓
Puff Count	↑	↑	↑	↑
TPM3 (mg/cig)	↓	↑	↑	↑
Ash Appearance	↔	↔	↔	↔
Taste	↑	↔	?	?

1 A) amount of tobacco combusted, B) rate of tobacco combustion,
C) more efficient trapping of smoke, D) more complete combustion
2 Static Burn Rate,
3 Total Particulate Matter

CONCLUSIONS

The amount of sidestream smoke depends on cigarette construction, tobacco blend, and paper properties.

The main paper properties affecting sidestream smoke generation are porosity, basis weight, type and amount of filler, and type and amount of burn additive.

The main pathways for reducing sidestream smoke are: reduce the amount of tobacco burned, slow down tobacco burn rate, trap a greater fraction of the smoke, and achieve more complete tobacco combustion.