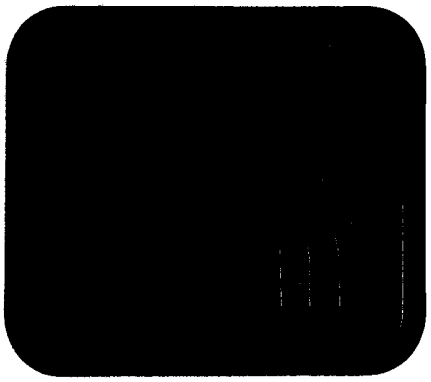

International Conference On The Physical And Chemical Processes Occurring In A Burning Cigarette

April 26-29, 1987

Graylyn Conference Center of Wake Forest University
Winston-Salem, NC USA

Sponsored by R.J. Reynolds Tobacco Co.

INTERNATIONAL CONFERENCE ON THE PHYSICAL AND CHEMICAL PROCESSES OCCURRING IN A BURNING CIGARETTE

ABSTRACTS

CONFERENCE SESSION I

STUDIES OF THE BURNING ZONE OF CIGARETTES

Keynote Lecture: SOME BURNING PROBLEMS IN TOBACCO SCIENCE

Richard R. Baker

British American Tobacco
(U.K. & Export) Limited
Southampton, England

The study of the science of cigarette burning processes begins with temperature measurements, since the formation of smoke products and the whole burning behaviour of the cigarette depends on burning zone temperatures and tobacco heating rate. A large number of studies have measured these parameters using a variety of techniques, including thermocouples, infra-red probes and infra-red cameras. Since the cigarette burning zone is a porous solid, the temperature distribution in two phases has to be measured: the solid and gas phases. These two phases are in near thermal equilibrium during the interpuff natural smoulder period, with the highest temperatures of around 800°C occurring in the centre of the zone. During puffing, the two phases have very different temperature distributions near the surface, although they are similar in the central regions (about 820-850°C).

Maximum solid-phase surface temperatures, up to 950°C, are observed on the burning zone periphery. Factors such as air influx and tobacco additives affect temperature and temperature gradients, and consequently such factors can have a significant effect on product formation.

Gas velocities inside the cigarette burning zone can be calculated from pressure and temperature distributions, and local velocities as high as 400 cm s^{-1} occur during puffing. Thus residence times in the higher temperature regions of the cigarette are typically less than one millisecond.

The high gas temperatures and velocities in the burning zone cause the characteristic increase in draw resistance of the cigarette when it is lit. This increase, and its subsequent variation during the smoking regime, has a direct influence on the amount of air drawn into the burning zone and subsequent combustion behaviour and product formation.

A series of studies has determined the regions inside the cigarette where products are released or formed. These studies have used small sampling probes inserted into the cigarette and connected directly to a mass spectrometer. The work has shown that the interior of the burning zone is oxygen deficient and hydrogen rich and can be effectively divided into two regions - an exothermic combustion zone and an endothermic pyrolysis/distillation zone. Oxygen-18 studies have shown that the oxides of carbon are formed in both zones. Semi-volatile components are, in general, released at temperatures between 300 and 600°C, although nicotine is released below 250°C. This is typically the region where the aerosol phase is forming inside the cigarette.

Similar probe studies have been conducted in the sidestream plume and temperature, gas concentration and velocity profiles have been determined. Little change occurs to the sidestream temperature and oxygen distributions when a puff is taken, indicating that the natural convection stream around the burning zone is only slightly affected by the influx of air during the puff. The sidestream gases rise from the cigarette burning zone in a fairly well-defined column which centres at about 3 mm in front of the paper burn line. On the other hand, the visible sidestream smoke column originates some 0 to 4 mm behind the paper burn line, becoming visible at temperatures below about 150°C.

Other processes occurring inside the cigarette such as gas diffusion and filtration of smoke particles have large effects on the final mainstream product levels. Relationships which include these mechanisms will be presented. Finally, as an indication of the complex inter-relationships of the dynamic processes occurring in the cigarette, the effect of ventilation on the various mechanisms will be presented.

MEASUREMENT OF TEMPERATURE DISTRIBUTIONS OF CIGARETTE COALS BY INFRARED IMAGING RADIOMETRY

Douglas D. McRae and R. W. Jenkins, Jr.

Philip Morris Research Center
Richmond, Virginia

and

J. S. Brenizer

University of Virginia
Charlottesville, Virginia

There are a number of thermal imaging systems available commercially that will convert the image of a scene or object as it appears in the infrared to a video signal that can be viewed on a television monitor. Since the infrared radiation emitted by an object is directly related to its temperature, one can, with reasonable care, use such an imaging system to measure temperature. This paper discusses the use of a thermal imaging system to measure the temperature distribution of a cigarette coal in real-time through the puffing cycle. The thermal camera was an Inframetrics Model 525 equipped with an 8-bit microprocessor to produce an image with 256 brightness levels (grey scale) for detailed temperature measurements. A special close-up lens was used to produce a magnified image of the coal. The video equipment supporting the thermal camera included a video tape recorder to store images for later analysis, a video timer that placed the date and time on each video frame and several video monitors. In addition, a digital image processor was programmed to analyze the recorded infrared images to extract the temperature distributions. The image processor could also produce a false color image of the coal from the original black and white picture. The false color images are especially useful for observing the temperature contours. The image processing programs will be covered discussed and preliminary results from the computer analysis will be presented.

EFFECT OF FLOW-FIELD ON THE MODE OF BURNING ZONE SPREAD ALONG CELLULOSIC MATERIAL

Kenji Sato and Setsuko Sega

Toho University
Japan

An experimental study has been conducted to explore the effect of flow-field on the mode of downward burning zone spread along a cylindrical cellulosic material in upward oxidizing flow. The spread rate and surface temperature of the burning zone spreading along a cylindrical cellulosic material of two different types were measured for several diameters as functions of oxygen concentration and free-stream velocity of the oxygen-nitrogen mixture flow, and the mode of burning zone spread were examined. Two types of cylinders used were rolled cardboard cylinder and rolled filter paper cylinder, along which the realized mode of burning zone spread in air were smolder spread and flame spread, respectively.

It was shown for the two types of cylinder that both of steady smolder spread and steady flame spread occur at certain appropriate combinations of oxygen concentration higher than that of air and free-stream velocity, i.e., bimodality of steady burning zone spread occurs widely in oxidizing flows due to the difference of the condition in an ignition procedure at the top of the cylinder. Based on the comparison of the variations of the burning zone spread rate, surface temperature, and limits of the bimodality or each spread mode, the effect of the flow-field on the mode of downward burning zone spread was discussed.

A SEMI-EMPIRICAL MODEL FOR SIMULATING THE EFFECT OF DESIGN COMPONENTS ON SMOKE DELIVERIES

Werner Schneider and A. Schlüter

British American Tobacco Cigaretten-Fabriken GmbH
West Germany

For the fast and economic assessment of the effects of different design components (e.g. cigarette paper, filter) on smoke and cigarette properties (e.g. nicotine delivery, puff number) computer based simulation models have been introduced within the cigarette and filter industry.

The presented semi-empirical model consists of three modules, which comprise the effects of ventilation, filtration and combustion. The description of these mechanisms is based partly on physical laws, partly on regressions.

By means of some examples the complex cooperating effects of conventional design components on the condensate delivery (e.g.) are illustrated. Another area of application is also illustrated by an example: the analysis of the contribution of a single design component to the deviations from given target values for smoke deliveries. This mostly cannot be identified by direct measurements.

AERODYNAMIC CHARACTERISTICS OF THE PLUME GENERATED BY A BURNING CIGARETTE

David P. Robinson

British American Tobacco
(U.K. & Export) Limited
Southampton, England

Quantitative information on the manner and rate at which smoke is transported away from a burning cigarette is extremely limited. Reference is invariably made to photometric studies, conducted in 1966, in which the velocity of a disturbance in the smoke plume was measured as it moved away from a cigarette. The spatially averaged velocity of 33 cm/s gave no information on the details of the velocity field carrying the aerosol particles generated by the smouldering cigarette.

In the investigations reported here, the three-dimensional velocity distributions in the sidestream plume in the vicinity of a burning cigarette have been measured with a laser Doppler velocimeter.

From the intensity of the light scattered by smoke particles in the vicinity of the plume, two distinct regions have been identified. Adjacent to the normally perceived visible smoke plume is a predominantly gaseous region in which very few particles exist. Velocity measurements across the width of the plume indicate that the visible sidestream smoke travels at a lower velocity than that of the particle-rare region and that the flow accelerates strongly as it moves away from the burning zone. The three-dimensional velocity field shows peak velocities in the region of 65 cm/s.

By combining the velocity data with calculated physical property variations, some integral properties of the plume have been evaluated. The monotonically increasing mass flow rates calculated in this manner are in reasonable agreement with an empirical correlation of natural convection plumes above heated cylinders.

MODELS OF CIGARETTE SMOKE FILTRATION

Gregory T. Rasmussen

Eastman Kodak Company
Kingsport, Tennessee

The modeling of cigarette smoke filtration has been an object of study since the introduction of cigarette filters more than thirty years ago. Currently, filters produced from cellulose acetate tow are a part of over half the tobacco cigarettes manufactured in the world. These filters are bundles of crimped and bonded fibers running the length of the filter. The filtration efficiency depends on fiber size and shape, the distribution and orientation of the fibers, the dimensions of the filter, and the smoking conditions. Mechanical filtration of particles accounts for most of the smoke captured. Some smoke components are selectively retained, and some smoke vapors condense on the filter as the burning coal approaches it. Numerous empirical models have been offered to relate efficiency to macroscopic filter construction variables. These models accurately estimate filtration efficiency for fibrous cellulose acetate filters when tested under standard smoking conditions. Models based on single fiber filtration efficiencies, which take a microscopic view of the system, have also been proposed. However, a number of obstacles prevent these models from achieving practical routine use. Advances in several areas may make it feasible to apply models derived from first principles to the estimation of cigarette smoke filtration efficiency for a wide variety of filters used over a range of smoking conditions.

CONFERENCE SESSION II

CHEMICAL MECHANISTIC STUDIES

Keynote Lecture: THE USE OF NUCLEAR RADIATION IN CHEMICAL MECHANISTIC STUDIES

Robert W. Jenkins

Philip Morris Research Center
Richmond, Virginia

The dawn of the atomic age occurred approximately eighty-five years after the publishing of a paper by T. Schloesing in which he reported on studies relating the inorganic composition of tobacco leaf to its burning qualities. Today the use of nuclear radiation has become common place in industry, government, our homes and in medicine. It is therefore logical that nuclear radiation has done much to help understand the chemical mechanisms taking place in the cigarette.

This paper will review the usages of nuclear radiation in studies on tobacco and cigarettes as they have been reported in the published scientific literature.

These literature reports will be covered under certain broad areas of research. These are:

1. Precursor-product studies
2. Cigarette construction and related effects on smoke
3. Cigarette component contributions
4. Tracer studies
5. Smoke composition vs. aerosol size
6. Cigarette air volumes
7. Instrumental neutron activation analyses
8. Cigarette rod density measurements
9. Neutron radiography

The results from these literature reports have been instrumental in establishing many significant conclusions about how smoke is formed and transferred out of the cigarette.

QUANTITATIVE NEUTRON RADIOGRAPHIC MEASUREMENT OF CONDENSABLES IN A BURNING CIGARETTE

Jack S. Brenizer, K. W. Tobin, and J. M. Hylko

University of Virginia
Charlottesville, Virginia

and

D. D. McRae and R. W. Jenkins, Jr.

Philip Morris Research Center
Richmond, Virginia

The real-time neutron radiography facility at the University of Virginia has been established in a project conducted jointly by the Department of Nuclear Engineering and Engineering Physics and the Philip Morris Research Center. The use of this system to measure the deposition of an aerosol in cellulose acetate filters and the relative density of tobacco cigarette rods has been previously reported. The technique for measuring absolute densities by neutron radiography has also been presented. In addition to these previous efforts, there has been an ongoing attempt to quantify the deposition of hydrogenous compounds along the axial direction of a burning cigarette. The observation of this deposition is complicated by the fact that inherent system noise tends to obscure the relatively small changes which occur in the cigarette rod. Software has been developed that takes into account the statistical nature of the neutron imaging system allowing for small variations in pixel luminance to be recorded real-time during the burn and correlated to an effective water density.

The data collection process is based on spatial grouping of pixel locations within the rod as well as a time averaged input of these discrete pixel groups. The information is collected during the puffing or smoldering of the cigarette. Once the system has been calibrated, the cigarette is positioned in the neutron beam. The rectangular area comprising the tobacco section of the rod is demarcated with the cursor. This area is then divided by the program into ten equal areas. All the pixel luminances in an area are averaged into one representative luminance value. As the cigarette burns, these ten areas are sampled at a predesignated time interval. A statistical analysis is performed for the live-time averages and the data is stored in a file for later analysis.

This technique was utilized to measure the effective water density changes in 2R1F research cigarettes burned under both puffing and smolder conditions. The effective water density-thickness distribution is presented and the axial density-thickness profile of the entire rod is shown for different times. The density-thickness increase is greatest near the burning end of the cigarette although there is a significant increase at the tobacco-filter interface.

THE BEHAVIOR OF GLYCEROL IN CIGARETTES DURING PUFF AND SMOLDER PERIODS

Fred W. Best

R. J. Reynolds Tobacco Company
Winston-Salem, North Carolina

The first part of this paper will discuss the total recovery smoking apparatus used in many of the radioisotope studies at RJR. Of prime importance among many modifications to a previously described system is a superior sidestream total particulate matter collection device.

Results of fate studies with a popular commercial filter tipped cigarette containing uniformly carbon-14 labeled glycerol at various locations within the cigarette and smoked with various puffing conditions will be discussed. In order to control mainstream and sidestream deliveries of smoke by cigarette design, an understanding of fates of major components during smolder and puffing periods is beneficial. Some studies to measure glycerol behavior during these periods have been undertaken and will also be discussed.

THE EFFECTS OF MIGRATION AND ELUTION ON MENTHOL DELIVERY IN CIGARETTES

Albert S. Eble

R. J. Reynolds Tobacco Company
Winston-Salem, North Carolina

Menthol is widely used as a cigarette flavorant and is thus a key ingredient in some top dressing formulations. The purpose of this work was to elucidate some of the mechanisms which control the delivery of menthol to smoke. Initial studies using ^{14}C-labeled menthol injected into unfiltered tobacco rods showed that menthol has a high transfer efficiency to mainstream (MS) smoke; about half of the applied radioactivity was recovered in the MS total particulate matter (TPM), and most of the remainder was found in the sidestream (SS) TPM and gas fractions. Under the same smoking conditions, less volatile flavors were delivered less efficiently to MS smoke and more efficiently to SS smoke. Experiments were performed to measure the elution efficiency of the various flavors in an attempt to explain the observed differences in MS deliveries. Application of radioactive flavors to the butt or unsmoked portion of an unfiltered tobacco rod demonstrated that about 32% of applied menthol was recovered in the MS TPM after 8 puffs, as compared to deliveries of less than 2% for the non-volatile flavors. More detailed experiments showed that only menthol which was located on tobacco less than 30 mm from the firecone was subject to elution by MS smoke.

Previous studies have shown that menthol applied to tobacco in filtered cigarettes migrates to the filter and vice versa. Furthermore, it is known that MS menthol delivery decreases with time parallel to this migration from rod to filter. Experiments designed to elucidate the mechanisms responsible for this decreased delivery showed that menthol in the filter is eluted less efficiently with increasing time due to absorption into the filter fibers. The age of the filter affected total menthol delivery but did not alter puff-by-puff delivery profiles. The age of the tobacco rod had no effect on menthol delivery.

In conclusion, the high volatility of menthol makes elution an important mechanism for menthol delivery and also causes rapid equilibration between rod and filter. This migration causes total menthol delivery to decrease with time due to absorption of the menthol by the filter fibers.

CONFERENCE SESSION III

PYROLYSIS STUDIES OF TOBACCO AND TOBACCO COMPONENTS

Keynote Lecture: The Pyrolysis and Combustion of Cigarette Constituents

Charles F. Cullis

The City University
London, England

The mechanisms of the pyrolysis of polymeric materials generally are affected by various factors, including in particular the heating rate, the absence or presence of oxygen and the nature and concentration of any additives. This is especially true in the case of cellulose (an important constituent of tobacco and the predominant constituent of cigarette paper), where the precise kinetic relationships observed depend also on the physical condition of the sample and the nature and flow rate of the surrounding gaseous atmosphere.

A description is therefore given of recent work on the pyrolysis and combustion of cellulose (both on its own and in contact with tobacco) under a wide range of experimental conditions designed to simulate as closely as possible those involved during the smoking of cigarettes. Special attention has been paid to the effects on the nature and distribution of the reaction products (particularly the carbon monoxide levels and tar and nicotine deliveries) of very high linear heating rates (up to 1200 deg s^{-1} and with final temperatures of up to 600-1300K), of the concentration of oxygen present and of a large number of inorganic salts and other additives.

CONTRIBUTION OF FRACTIONATED TOBACCO EXTRACTS TO PYROLYTIC GAS PHASE CONSTITUENTS

Harold R. Burton

University of Kentucky
Lexington, Kentucky

There has been interest in the contribution of various tobacco constituents to the composition of cigarette smoke. A study was initiated to determine if the removal of soluble tobacco constituents by solvent extraction influenced the tar yield of 1R1 cigarettes. This study also included the extraction of 1R1 tobacco with acetone and fractionation of the extract into a non-polar, moderately polar and polar fraction. Differential thermogravimetry (DTG) of the non-fractionated and fractionated extracts revealed there were significant differences between the weight loss of these extracts. Temperature yield profiles for the gas phase constituents from these extracts were determined by pyrolysis gas chromatography (PGC) and by DTA. The fractionated extracts in various concentrations were added to blended tobacco and cigarettes were manufactured from these modified tobaccos. Data will be presented for smoke analyses, DTG and PGC.

PYROLYSIS OF BULK SAMPLES OF CELLULOSE

Merwin Sibulkin

Brown University
Providence, Rhode Island

The investigation of flaming combustion of fuels can usefully be divided into studies of gas-phase diffusion flames and solid-phase pyrolysis. In this paper we examine the pyrolysis of cellulose to determine its rate of gasification and heat of gasification (which is a quasi-property connecting the gas and solid phase processes). A theoretical analysis of the propagation of a one-dimensional pyrolysis wave into a bulk sample of cellulose is described. The results of numerical solutions of the governing equations are discussed with emphasis on the effects of variations in the material properties. It is found that the char density and thermal conductivity have a strong effect on total pyrolysis rate while the specific reaction rate has a weaker effect. A new experimental set-up for studying bulk pyrolysis in an inert atmosphere is described, and some of the problems encountered are discussed. Measurements of pyrolysis rate and heat of gasification are presented for both pure cellulose and cellulose with a fire-retardant additive. The theoretical and experimental results are compared, and the role of the additive is discussed.

EFFECT OF TEMPERATURE ON PRODUCTS FROM THE RAPID PYROLYSIS OF CELLULOSE

Donald S. Scott, Jan Piskorz and Desmond Radlein

University of Waterloo
Waterloo, Ontario, Canada

The same sample of Avicel microcrystalline cellulose has been pyrolyzed in two different reactors -- a fluidized bed and a transport reactor -- by two different research groups over a temperature range of 450°C-900°C. Pyrolysis data for a constant vapor residence time of 0.5 seconds are shown to agree for the two cases.

Liquid products were analyzed and results are shown for the changing concentrations of major components of the liquid as a function of temperature at constant reaction time. Some speculations can be made concerning possible sequences of the homogeneous decomposition reaction steps occurring.

CONFERENCE SESSION IV

STUDIES OF SMOLDERING COMBUSTION

Keynote Lecture: ASPECTS OF SMOLDERING COMBUSTION

Thomas J. Ohlemiller

Center for Fire Research
National Bureau of Standards
Gaithersburg, Maryland

The process of smoldering combustion is encountered in several contexts in addition to cigarette burning e.g., fire safety and underground coal gasification. The behavior of this combustion mode in some of these contexts will be briefly reviewed to reveal the effects of fuel type and configuration. Features common to such problems will be noted. These serve to introduce the generalized problem of modeling smolder propagation. The elements of such a general model will be reviewed, with an emphasis on the thermophysics. Existing propagation models will be examined in light of this general model. The inadequacies of one-dimensional models for the multi-dimensional, real-world smolder problems will be discussed.

NON-DARCY FLOW AND DIFFUSION IN A TOBACCO ROD

Richard R. Baker and D. P. Robinson

British American Tobacco
(U.K. & Export) Limited
Southampton, England

A mathematical model of the steady state convection-diffusion processes which control the concentration of gas phase components in unlit cigarettes is presented. The cigarette is modelled as a cylindrical rod of porous material surrounded by a naturally permeable membrane. Account is taken of the non-Darcian nature of the flow through the tobacco and an analytical solution found for the resultant nonlinear problem. The mass transfer processes are modelled by a convection-diffusion equation and a numerical method of solution is presented. Experiments on unlit cigarettes are briefly described and comparisons between the experimental and theoretical results are shown to confirm the validity of the model. The influences of the various cigarette parameters on the mass transfer processes are elucidated.

THE SMOLDERING COMBUSTION OF CELLULOSIC AND STARCH DUSTS

S. O. Leisch, C. William Kauffman, and M. Sichel

The University of Michigan
Ann Arbor, Michigan

Finely divided solid organic material is of considerable interest from the combustion viewpoint. Oxidation may occur via three radically different processes -- smoldering, deflagration, or detonation. The rate of reaction front propagation between the slowest and fastest process differs by typically nine orders of magnitude!

Smoldering combustion occurs at high equivalence ratios. The fuel may be heaped, in layers, or in a well defined cylinderical geometry. The ventilation may be natural or forced. The purpose of this work is to examine the ignition and propagation of a smoldering combustion process through deep horizontal layers of grain and wood dust.

Combustion wave velocities have been measured as a function of material, ignition source depth, and wave depth, with and without a forced horizontal airflow over the layer surface which ventilates the layer and which may initiate the appearance of an open flame. The wave velocity is found to be affected by the material, the void fraction, the depth, and the ventilation.

Minimum ignition energies as a function of power per unit area have been measured for the dusts. For intermediate power and energy conditions the ignition is found to be statistical in nature. Optimum ignition conditions may be defined.

A numerical solution for the conservation equations describing a one dimensional smoldering combustion wave has been obtained. The results for cellulose are in good agreement with measured wave details -- velocity and temperature and density profiles. For starch dust it is possible to estimate some kinetic data through the fitting of experimental data.

While this effort has provided useful information with regard to the smoldering combustion process, many new interesting questions and ideas have been raised.

CONFERENCE SESSION V

AEROSOL PROPERTIES, FORMATION, TRANSPORT AND DYNAMICS

Keynote Lecture: AEROSOL PROPERTIES, FORMATION, TRANSPORT AND DYNAMICS

E. James Davis

University of Washington
Seattle, Washington

Recent advances in the development of equipment and techniques for the study of the chemistry and physics of aerocolloidal matter are emphasized in this talk. Of particular relevance are the electrodynamic balance and optical trap which have been used or can be used for a wide variety of studies of single microparticles and microdroplets, including smoke particles. A brief introduction to the principles of these devices will be provided, and then their application to studies of evaporation/condensation and nucleation processes, aerodynamic drag forces and photophoretic forces on particulate matter, microdroplet infrared spectroscopy, and elastic and inelastic light scattering will be described. The light-scattering applications include conventional elastic scattering as well as Raman and fluorescence spectroscopy. Elastic scattering measurements can yield size and refractive index information for smoke particles, but Raman and fluorescence techniques can provide a wealth of chemical information. Although Raman and fluorescence spectroscopies of microparticles are in their infancies and involve sophisticated problems associated with interpreting spectra, they show great promise for examining the chemistry of smoke particles and combustion products. Application of microparticle fluorescence measurements to follow the kinetics of a free-radical reaction in a microdroplet will be presented. A new application of the electrodynamic balance, which is the measurement of the radioactivity of a microparticle, will be introduced. This has relevance to the use of radioactive tracers in tobacco research. This presentation will close with a summary of research needs in the field of aerocolloidal particles.

PARTICLE SIZE MEASUREMENTS OF MAINSTREAM TOBACCO SMOKE USING A LIGHT EXTINCTION SPECTROMETER

Kenneth A. Cox and Constance H. Morgan

Philip Morris Research Center
Richmond, Virginia

The mainstream tobacco smoke aerosol from the Kentucky Reference 2R1 cigarette is studied using a spectral extinction technique. Extinction spectra obtained as frequently as every 5 msc with a diode array spectrometer are used to determine both the aerosol mean particle size and the aerosol mass concentration. The measurements are made at the exit of the cigarette without the need for dilution. By comparing the aerosol mass concentration determined from the extinction measurements with TPM subsequently collected on a Cambridge pad, a determination is also made of the condensable vapor component of the smoke. The results presented include measurements of the mean aerosol particle size and the fraction of condensable vapor delivered as a function of puff position. Also presented are the aerosol mass concentration and mean particle size as a function of time during a puff.

GROWTH AND EVAPORATION OF HYGROSCOPIC AEROSOLS

Asit K. Ray

University of Kentucky
Lexington, Kentucky

and

Brown & Williamson Tobacco Corporation
Louisville, Kentucky

Growth and evaporation of single hygroscopic aerosols have been measured at various relative humidities. Two types have been examined -- cigarette smoke particles and glycerol droplets. The experiments were conducted in an electrodynamic balance where a charged droplet was suspended in a jet of air flowing at a constant velocity. At the null point of the electrodynamic balance, the weight of the droplet was exactly balanced by the net force created by the aerodynamic drag and the electric field due to the d.c. voltage applied across the endcap electrodes of the balance. The humidity and temperature of the air in the jet surrounding the droplet was controlled precisely. In a typical experiment, the humidity was altered from 0 to 80% in steps of 10%, and thus, the same droplet was exposed to various humidity levels. After each step increase in humidity, the droplet size and mass as functions of time were obtained from the light scattering and balancing d.c. voltage.

Cigarette smoke particles showed erratic behavior when exposed to high humidity levels. Some particles grew, and others did not show any appreciable change in size. The data indicates that cigarette smoke may be composed of two types of particles -- one type contains hygroscopic component(s), and the other type is devoid of any hygroscopic material.

For a glycerol droplet, after a step increase in the humidity level, the droplet grew to a maximum size and then evaporated. From the experimental data, we draw the following conclusions:

(i) For a given humidity, the maximum water content in a droplet is always lower than the value predicted by the glycerol-water bulk equilibrium data.

(ii) The time required by a droplet to reach the maximum size is considerably higher than the time predicted by the diffusion theory.

(iii) During the evaporation period, for a given humidity, the ratio of glycerol to water in a droplet remains constant and is equal to that at the maximum size. The evaporation behavior of the droplet is identical to that of a single component droplet (i.e., the square of the droplet diameter changes linearly with time).

SMOKE PARTICLES PRODUCED FROM TOBACCO CELL WALL COMPONENTS

Yoshiaki Ishizu, Kazuyo Kaneki, and Takeshi Sakaki

Japan Tobacco Inc.
Yokohama, Japan

Smoke particle production from each tobacco cell wall component was investigated. Four major components of cell wall, -cellulose, hemicellulose, lignin and pectin, were isolated from cured tobacco leaves. They were heated in a thermobalance in the atmospheres of air and helium, at the heating rates of 10°C/min and 240°C/min. The sizes and the weights of the produced smoke particles and the weight losses of the samples were measured simultaneously.

The median curves of the smoke particle sizes from -cellulose, hemicellulose and pectin showed similar curve patterns of the production rate. It was shown that the smoke particle sizes from them correlated to their particle concentrations.

-Cellulose and lignin could produce more smoke particles than hemicellulose and pectin. Under similar conditions to a burning cigarette, in helium and at 240°C/min, the total weights of smoke particles per 1mg of the samples were 0.32mg for -cellulose, 0.24mg for lignin, 0.03mg for hemicellulose and 0.004mg for pectin. -Cellulose, the largest component in tobacco cell wall, had the highest smoke particle producing rate. It can be concluded that -cellulose contributes the most to smoke production of a burning cigarette.

COAGULATION AND FILTRATION OF MAINSTREAM CIGARETTE SMOKE IN THE TOBACCO ROD OF A CIGARETTE

David W. Boldridge and Bradley J. Ingebrethsen

R. J. Reynolds Tobacco Company
Winston-Salem, North Carolina

Mainstream cigarette smoke is a highly concentrated aerosol that undergoes both coagulation and filtration as it travels through a tobacco rod. Measurements of the particle size distribution and number concentration of mainstream smoke were made during a puff for a series of tobacco rod lengths. A model was developed which predicts the changes in the cigarette smoke aerosol as it travels through a length of tobacco rod. The model is based on simple equations for filtration and coagulation of aerosols.

The experimental apparatus used in this work measures the particle size distribution of a fresh, undiluted sample of mainstream smoke by ensemble light scattering. Five detectors placed at 30^{0}, 60^{0}, 90^{0}, 120^{0}, and 150^{0} relative to the interrogating laser beam (Argon ion, 514 nm) measure the scattered light intensity. Ratios of these intensities (relative to the intensity at 90^{0}) are compared to tabulations of Mie scattering values for log-normally distributed aerosols with a refractive index of 1.54-0.0i to obtain best-fit values of the geometric mean diameter and geometric standard deviation. The number density is obtained from the absolute scattering intensity and the theoretical scattering efficiency at 90^{0} and the gravimetrically determined wet total particulate matter for each puff. The measurement is repeated every 20 ms to determine the time resolved profile during the two-second puff. Data were acquired for the second puff on tobacco rods ranging from 49 mm to 119 mm in length. Details of the experimental procedure have been presented elsewhere. (Ingebrethsen, 1986)

The model uses an initial set of experimentally determined size distribution and number density parameters as input data. The only other input parameters are the physical characteristics of the tobacco rod (cross-sectional area, void volume, tobacco rod length, effective fiber diameter, etc.) and the smoke flow rate. The effective fiber diameter was determined from the relationship of pressure drop to flow rate.

The evolution of the size distribution and number density is predicted by calculating the filtration and coagulation of the initial aerosol as it travels through the tobacco rod. The filtration model was constructed using single fiber filtration equations (Hinds, 1982) and the coagulation model was built around analytical expressions for Brownian coagulation in the continuum regime (Lee, 1983). Log-normal aerosol distributions were assumed throughout the model.

The mean mass diameter becomes larger as the length of the tobacco rod increases, while the number density decreases dramatically. The predicted values of the mean mass diameter and the number density are in good agreement with experimentally determined values.

Hinds, W. C. Aerosol Technology. John Wiley and Sons, New York (1982).

Ingebrethsen, B. J. "Evolution of the Particle Size Distribution of Mainstream Cigarette Smoke During a Puff". AEROSOL SCI. TECH. 5:423 (1986).

Lee, K. W. "Change of Particle Size Distribution During Brownian Coagulation". J. COLL. INTERFACE SCI. 92:315 (1983).