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Thermal Emissivity and Cigarette Coal Temperature During Smolder*

by

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SUMMARY

Coal temperatures affect the burn properties of cigarettes. Thermal imaging was used to determine the average maximum surface coal temperatures during smolder of cigarettes of different tobacco types. The thermal imaging camera was calibrated against a reference blackbody. An emissivity correction was necessary since the set point temperatures of the reference blackbody did not correspond to the measured temperatures of the reference blackbody. A 0.87 camera emissivity was applied to provide accurate coal temperatures at a corrected emissivity of approximately 1.

The average maximum surface coal temperatures during smolder of unfiltered single-tobacco-type cigarettes and a commercial blend cigarette were determined (with the camera lens focused parallel to the cigarette), and no discernible differences among them were found. The calculated average maximum surface coal temperature during smolder for all cigarettes was 584 ± 15 ˚C. During smolder, thermocouples were used to measure the temperature of the gas phase (along the central axis of coal), and the thermal imaging camera was used to measure the temperature of the solid phase of the coal's surface. Using thermocouples, the peak coal temperatures in the center of the coal during smolder for three filtered single-tobacco-type cigarettes were 736–744 ˚C. Peak coal temperatures, measured by thermal imaging, on the surface of the coal (with the camera lens focused coaxially with the coal and the ash removed) for the same three single-tobacco-type cigarettes had a range of 721–748 ˚C. There was good correspondence between the two techniques. These results confirm that during smolder the gas-phase temperature inside the coal (as measured with the thermocouple) and the solid-phase temperatures beneath the ash (as measured with the camera) are in near thermal equilibrium. With proper calibration, a thermal imaging system is a good alternative to thermocouples for measuring cigarette coal temperatures. [Beitr. Tabakforsch. Int. 20 (2003) 381–388]

ZUSAMMENFASSUNG

Die Temperatur der Glutzone hat einen Einfluss auf die Brenneigenschaften von Zigaretten. Mit Hilfe thermischer Bildgebungsverfahren wurden während des Glimmens von Zigaretten unterschiedlicher Tabaksorten die durchschnittlichen maximalen Temperaturen an der Oberfläche der Glutzone bestimmt. Die thermische Kamera wurde auf einen schwarzen Körper, der als Referenz diente, geeicht. Eine Korrektur des spezifischen Emissionsvermögens war notwendig, da der Sollwert des als Referenz dienenden schwarzen Körpers nicht den gemessenen Temperaturen des schwarzen Körpers entsprach. Um präzise Temperaturen eines korrigierten Emissionsvermögens von ungefähr 1 zu erhalten, wurde ein Emissionsvermögen der Kamera von 0,87 eingestellt.

Die durchschnittlichen maximalen Temperaturen an der Oberfläche des Glutzone während des Glimmens filterloser, aus einer Tabaksorte bestehender Zigaretten und einer handelsüblichen Blendzigarette wurden bestimmt (wobei die Linse der Kamera parallel zur Zigarette fokussiert wurde); dabei wurden zwischen den untersuchten Zigaretten keine erkennbaren Unterschiede festgestellt. Die berechnete durchschnittliche maximale Temperatur an der Oberfläche der Glutzone lag bei allen glimmenden Zigaretten bei 584 ± 15 ˚C. Mit Hilfe von Thermoelementen wurde während des Glimmens die Temperatur der Gasphase (entlang der Mittelachse der Glutzone) und mit der thermischen Kamera die der Festphase an der Oberfläche der Glutzone gemessen. Mit Hilfe der Thermoelemente wurden bei drei Filterzigaretten, die aus einer Tabaksorte bestanden, in der Mitte der Glutzone während des Glimmens Temperaturspitzen von 736–744 ˚C bestimmt. Die mit Hilfe der thermischen Kamera ermittelten Temperaturspitzen an der Oberfläche der Glutzone betrugen bei denselben drei Zigaretten 721–748 ˚C, wobei die Linse der Kamera koaxial zur Glutzone ausgerichtet und die Asche und die Kohleentfernt wurden. Die beiden Techniken zeigten gute Übereinstimmung. Diese Ergebnisse bestätigen, dass bei glimmenden Zigaretten die Temperatur der Gasphase im Inneren des Glutkegels (wie mit Hilfe der Thermoelemente gemessen), und die Temperaturen der Festphase unterhalb

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der Asche (wie mit Hilfe der Kamera gemessen) sich annähernd in einem thermischen Gleichgewicht befinden. Bei geeigneter Kalibrierung ist zur Temperaturbestimmung der Glutzone einer Zigarette eine thermische Kamera eine gute Alternative zu Thermoelementen. [Beitr. Tabakforsch. Int. 20 (2003) 381–388]

RESUME

La température du cône de combustion influence les propriétés de combustion d' une cigarette. Par une méthode de visualisation thermique les températures maximales moyennes à la surface du cône de combustion de cigarettes en combustion confectionnées avec différents types de tabacs ont été déterminées. La caméra thermique a été étalonnée par rapport à un corps noir de référence. Une correction de la capacité d' émission a été nécessaire, parce que les températures fixées du corps noir de référence ne correspondaient pas aux températures mesurées de celui-ci. Une capacité d' émission de la caméra de 0.87 a été appliquée pour recevoir des températures précises du cône de combustion d' une capacité d' émission corrigée d' environ 1.

Les températures maximales à la surface du cône de combustion de cigarettes en combustion confectionnées avec un seul type de tabac et une cigarette de mélange disponible sur le marché ont été déterminées, l' objectif de la caméra étant centrée parallèlement à la cigarette ; et aucune différence visible entre les cigarettes n' a été trouvée. La température maximale moyenne calculée à la surface du cône de combustion pendant la combustion est de 584 ± 15 ˚C pour toutes les cigarettes. La température de la phase gazeuse des cigarettes en combustion a été mesurée avec des thermocouples (parallèlement à l' axe centrale du cône de combustion), et la température de la phase solide à la surface du cône de combustion a été déterminée avec la caméra thermique. Les températures maximales mesurées à l' aide des thermocouples au centre du cône de combustion de cigarettes en combustion est de 736–744 ˚C chez les trois cigarettes avec filtres confectionnées avec un seul type de tabac. Les températures maximales mesurées à la surface du cône de combustion à l' aide de la caméra thermique (l' objectif de la caméra étant centrée de façon coaxiale sur le cône de combustion et la cendre étant écartée) chez les mêmes cigarettes est de 721–748 ˚C. Les résultats obtenus avec les deux techniques sont en bon accord. Les résultats confirment que la température de la phase gazeuse au centre du cône de combustion (mesurée par thermocouple), et les températures de la phase solide sous la cendre (mesurée par caméra thermique) sont en quasi-équilibre thermique. Avec un étalonnement propre la caméra thermique constitue une bonne alternative aux thermocouples pour les mesures de température du cône de combustion des cigarettes. [Beitr. Tabakforsch. Int. 20 (2003) 381–388]

INTRODUCTION

The objective of these experiments was to determine the average maximum coal temperature during smolder for single-tobacco-type and commercial blended cigarettes using a thermal imaging camera technique. Additional experiments were conducted to compare the peak coal temperature measured during smolder with thermocouples and with thermal imaging.

The Stefan-Boltzmann law

$$W = \varepsilon\sigma A T^4$$

states that the total energy radiated per unit surface area of a blackbody, in unit time, is obtained from integration of Planck's law of radiation over all wave lengths, where W is equal to the radiated power, ε is emissivity, σ is the Stefan-Boltzmann constant, A is the area, and T^4 is the measured Kelvin temperature for the blackbody taken to the 4^{th} power. Emittance is a fundamental parameter in Planck's radiation formula. Emittance (the energy radiated by the surface of a body per second, per unit area) is a fundamental property of a substance, dependent upon its surface characteristics (finish), thickness, and the specific wavelength of light emitted from the source at some temperature (1). Emittance and emissivity should not be confused. Emissivity is defined as the ratio of the radiation emitted by a surface to the radiation emitted by a blackbody at the same temperature over all wavelengths. By definition, the emissivity of a blackbody is 1 (1,2). We are assuming the reference blackbody closely approximates a blackbody. As material properties differ, emissivities can differ as well (2). LENDVAY and LASZLO (3) determined cigarette peak coal temperature during intermittent puffing by utilizing a thermal imaging camera system with a camera emissivity setting of 0.98. This emissivity setting provided good agreement between the set point and measured temperatures of a reference blackbody. Their subsequent work (1) employed a radiometric procedure and determined that the emittance of a cigarette coal during smolder closely approximated the emittance of a reference blackbody. They concluded that an emittance correction was unnecessary when using their infrared method and that the average emissivity for the cigarette coal was between 0.91 and 0.997 (1).

LENDVAY and LASZLO (3) reviewed prior work on the measurement of cigarette peak coal temperatures measured during active puffing. Nearly all of the work prior to their study was done with thermocouples of various types and diameters on cigarettes containing various tobaccos or blends of tobacco in a variety of cigarette configurations. The temperature range reported for cigarette peak coal temperature during active puffing was 656–1050 ˚C (3). The range of temperatures reported for cigarette maximum coal temperature during smolder was 316–900 ˚C (4,5,6). Although not discussed in their paper, LENDVAY and LASZLO (3) showed thermograms of peak temperatures of cigarette coals as a function of puff numbers where cigarette smolder temperatures can be estimated. Typically, they reported maximum average coal temperatures during smolder in the range of 580–590 ˚C.

EXPERIMENTAL AND METHODOLOGY

Cigarettes

A series of unfiltered cigarettes was prepared containing a single tobacco type as described in Table 1. The cigarettes

Table 1. Description of cigarettes for measurement of average maximum coal temperature during smolder

Code	Description
O	A common group blend of Oriental tobaccos in an 83-mm unfiltered cigarette configuration
B1	A common group blend of burley tobacco in an 83-mm unfiltered cigarette (contains low stalk burley tobacco)
B2	A common group blend of burley tobacco in an 83-mm unfiltered cigarette (contains upper stalk burley tobacco)
B0	A common group of burley tobacco in an 83-mm unfiltered cigarette (contains off-shore[a] burley tobacco)
FC1	A common group blend of flue cured tobacco in an 83-mm unfiltered cigarette (contains lower stalk flue-cured tobacco)
FC2	A common group blend of flue cured tobacco in an 83-mm unfiltered cigarette (contains upper stalk flue-cured tobacco)
RTS	A reconstituted tobacco sheet (RTS) in an 83-mm unfiltered cigarette. RTS was prepared from 68% stems (75% flue-cured and 25% burley) and 32% mixed scrap and dust
CRES	A common group type of cut, rolled, expanded, and shredded (CRES) flue-cured stem in an 83-mm unfiltered cigarette
Commercial	A commercial, ventilated filtered, 84-mm American blended cigarette

[a]Off-shore tobaccos are imported tobaccos from international sources.

were of standard circumference (approximately 24.8 mm) and 83 mm in length. Additional cigarette characteristics and measurements are listed in Table 2. All cigarettes were conditioned at 24.4 ˚C and 60% RH for at least 24 h prior to testing. A second set of test cigarettes was prepared to compare the peak coal temperature measurements of thermocouples with a thermal imaging camera during smolder. Descriptions of the filtered cigarettes are in Table 3. Additional cigarette characteristics and measurements are listed in Table 4.

Equipment and techniques

An Agema ThermoVision 900 SW-TE thermal imaging camera (Agema Infrared Systems, Sweden) was used to collect the thermal imaging data. The ThermoVision 900 was interfaced with a Vectra VE C/300A computer (Hewlett-Packard, Palo Alto, CA) equipped with a ThermoVision 900 PC Card Interface and power scanner by Agema. ThermaCAM software (FLIR Systems, Boston, MA) was installed onto a Windows 98 (Microsoft Corporation, Redmond, Washington) operating system to operate the camera and program the collection protocol. Environmental conditions, lens distance, and emissivity setting were variable parameters included in the software package. Cigarette coal temperature data were collected every 2 sec for 30 sec. Multiple readings were collected and averaged for each experiment. The reference blackbody radiator used in these experiments was an Omega BB4A (Omega Engineering, Inc., Bridgeport, NJ) with a temperature range of 110–982 ˚C. Reference blackbody temperatures were collected at a rate of one per second for 30 sec. Multiple readings were collected and averaged for each experiment. All experiments were conducted under laboratory conditions of 24.4 ˚C and 60% RH.

Calibration of the thermal imaging camera

Thermal emissivity is inversely related to the temperature of a reference blackbody radiator. Reported coal temperatures are too low if the thermal imaging camera emissivity set is too high. Initially, the thermal imaging camera used in these experiments showed low correspondence between the reference blackbody set point temperatures and the reference blackbody temperatures. When an arbitrary

Table 2. Analyses of single-tobacco-type cigarettes for measurement of average maximum coal temperature during smolder

Code	O	B1	B2	BO	FC1	FC2	RTS	CRES	Commercial
				Cigarette analyses					
Length (mm)	83	83	83	83	83	83	83	83	84
Weight (g)	1.327	0.966	1.161	0.967	1.222	1.364	1.011	1.147	0.938
Circumference (mm)	24.89	24.83	24.84	24.81	24.87	24.81	24.86	24.85	24.84
				Smoke analyses					
Puffs/cig	15.6	8.1	10.9	8.2	12.4	15.2	7.0	6.0	7.8
TPM (mg/cig)	40.5	33.3	40.1	31.3	39.4	52.1	20.2	10.8	13.1
Nicotine (mg/cig)	1.44	3.73	5.03	2.61	3.08	4.55	0.64	0.31	0.87
Water (mg/cig)	5.2	3.8	4.7	3.4	3.5	5.0	2.7	1.5	1.42
“Tar” (mg/cig)	33.9	25.8	30.4	25.3	32.8	42.6	16.9	9.0	10.8
CO (mg/cig)	16.2	18.1	20.2	20.3	17.0	18.5	22.1	13.9	12.5
CO_2 (mg/cig)	63.6	51.1	64.7	52.7	60.3	64.5	49.2	38.1	40.0
				Burning rate (BR)					
BR (mg/min)	44.40	51.62	48.74	54.10	46.44	46.91	87.31	85.55	61.51
BR (mm/min)	2.75	4.55	3.79	4.63	3.24	2.95	6.35	7.70	4.82

Table 3. Description of filtered single-tobacco-type cigarettes for measurement of peak coal temperature using thermocouples and thermal imaging[a]

Code	Description
OF	A common group blend of Oriental tobacco in an 84-mm filtered cigarette configuration
BF	A common group blend of upper stalk burley tobacco in an 84-mm filtered cigarette configuration
FCF	A common group blend of upper stalk flue-cured tobacco in an 84-mm filtered cigarette configuration

[a]All cigarettes had a 27-mm cellulose acetate filter with 25% filter ventilation.

Table 4. Analyses of single-tobacco-type cigarettes for measurement of average coal temperature using thermocouple and thermal imaging

Code	OF	BF	FCF
Cigarette analyses			
Length (mm)	84	84	84
Weight (g)	1.183	1.028	1284
Circumference (mm)	24.84	24.82	24.98
Smoke analyses			
Puffs/cig	15.5	10.5	19.1
TPM (mg/cig)	20.2	15.9	147
Nicotine (mg/cig)	2.15	2.15	0.72
Water (mg/cig)	1.6	1.3	1.3
"Tar" (mg/cig)	16.5	125	12.7
CO (mg/cig)	11.2	12.0	10.2
CO_2 (mg/cig)	50.2	47.4	51.8
Burning rate (BR)			
BR (mg/min)	38.09	44.44	42.40
BR (mm/min)	2.16	3.06	216

camera emissisivity setting of 0.92 was used [an emissivity level within the range specified by LENDVAY and LASZLO (1)] the measured temperature of the reference blackbody was lower than expected. It is believed that the Agema ThermoVision camera, although originally calibrated from the factory, had lost its factory calibration settings. Regardless, as in any analytical measurement, it is extremely important to properly calibrating the measuring instrument. To determine the correct camera emissivity setting that produced accurate temperature measurements for the reference blackbody, a matrix of set point temperatures of the reference blackbody and thermal camera emissivities was developed (Table 5). Reference blackbody data were collected across a range of 300˚ (550–850 ˚C) and five emissivities (0.99–0.60). The measured temperatures of the reference blackbody decreased with increasing emissivities at each set point temperature of the reference blackbody (Figure 1). Across an emissivity span ranging from 0.99 to 0.80, the temperature values moved 4.5% or less from the set point. This represents a 14–39 ˚C change in absolute temperature. Examination of reference blackbody data with emissivity values of 0.99, 0.92, 0.80, 0.70, and 0.60 showed that for set point temperatures of 550 ˚C or more, the set point fell between temperature measurements made with emissivities of 0.80 and 0.92. Linear interpolation of the set point between temperatures at these emissivity settings provided emissivity estimates between 0.87 and 0.88 (i.e., 0.88 ± 0.002) for set points of 560 ˚C and above, with 0.87 at 550 ˚C. These results suggest that emissivity around 0.87–0.88 is appropriate for the reference blackbody in this temperature range. Calculation of difference and percent change between consecutive emissivity levels tested (0.99 to 0.92, 0.92 to 0.80, 0.80 to 0.70, and 0.70 to 0.60) showed increased differences as the temperature increased, but consistent percentage changes. After an analysis of the data, an emissivity camera setting of 0.87 was selected. This emissivity setting provided accurate measurements of the reference blackbody set point temperatures. All

Table 5. Average measured temperature (˚C) of reference blackbody at varying emissivity at selected reference blackbody set point temperatures

	Emissivity					Estimated temperature at 0.87 emissivity
Set point temperature (˚C)	0.99	0.92	0.80	0.70	0.60	
550	526	539	564	590	622	550
560	537	550	576	602	635	559
570	546	560	586	613	646	569
580	556	569	597	624	658	579
590	566	579	607	636	670	589
600	575	590	618	647	683	599
610	584	599	628	658	694	609
620	594	609	639	669	706	619
630	603	618	649	680	718	629
640	613	628	659	691	730	639
650	622	638	669	702	742	649
750	716	736	775	814	864	750
850	811	833	880	928	987	850

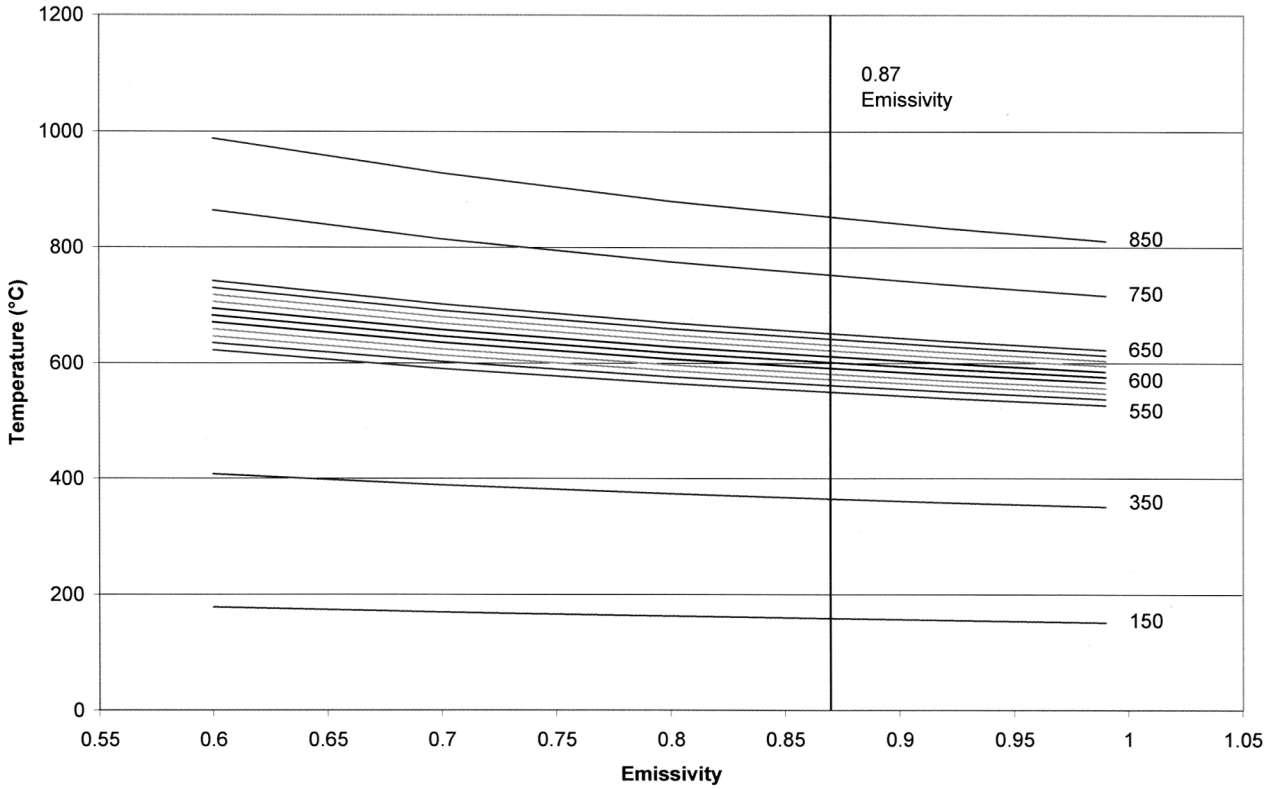

Figure 1. Emissivity/temperature study: Measured blackbody at varying set points across a range of emissivities

measurements in this report used the camera emissivity setting of 0.87 and have a corrected emissivity of 1.

Measurement of average smolder coal temperatures

The average smolder coal temperature is the average temperature of the coal's surface measured with the camera lens focused parallel to the cigarette and the ash left undisturbed. Conditioned cigarettes were oriented perpendicular (side view) to the camera body and parallel to the lens surface. Cigarettes were positioned horizontally at a distance of 36.5 cm from the camera lens. The cigarettes were then lit, puffed once (35-cc puff for 2 sec), and allowed to smolder at least 15 mm before coal temperatures were measured across a range of emissivities. Each cigarette type was run in triplicate, at each of five camera emissivity settings (0.99, 0.92, 0.80, 0.70 and 0.60). Temperature readings were collected every 2 sec for 30 sec. A minimum of three measurements was performed for each experimental point. Analysis of variance was conducted to compare the change in average temperature with emissivity among cigarettes.

Measurement of peak smolder coal temperatures

Peak smolder coal temperatures are the peak temperatures detected on the surface of the coal with the camera lens focused on the end of the coal, in an axial direction and with the ash removed. The cigarettes were viewed by the thermal imaging camera in a field parallel (coal face on) to the camera body and perpendicular to the lens surface. Cigarettes were positioned horizontally. Each cigarette was lit, puffed once (35-cc puff for 2 sec), and allowed to burn back 30 mm prior to data acquisition. The peak smolder coal temperature was recorded after tapping off the ash when the coal was 36.5 cm from the lens. A minimum of three measurements was performed for each experimental point. Averages and standard deviations were calculated for each data set.

Thermocouple equipment and technique

In an additional experiment, peak smolder coal temperatures were measured with a type "E" "fast response" thermocouple (Chromega/Constantan bead on 0.25 mm stainless steel wire, Omega Engineering, Model 304SS, Stamford, CT). The three cigarettes described in Table 3 were tested. Three thermocouples were inserted in the center region of each cigarette rod along the longitudinal axis of the cigarette about 7 mm apart. Cigarettes were prepared in a manner similar to that employed by employed by TOUEY and MUMPOWER (7). The cigarettes were lit, puffed twice (35-cc puff for 2 sec), and allowed to smolder in a horizontal position in air. As the coal passed each thermocouple as the cigarette smoldered, thermocouple data were continuously collected via a data collection computer program that logged time and voltage and converted voltage to temperature. The smolder temperatures were thereby recorded as a function of time (and thus position). The peak smolder coal temperatures were obtained by examining the temperature/time data.

RESULTS AND DISCUSSION

Thermal imaging experiments

Measurement of average maximum coal temperatures for single-tobacco-type and commercial cigarettes: Because material properties determine sample-specific emissivities,

Table 6. Average maximum coal temperature (˚C) of single-tobacco-type and commercial cigarettes at varying emissivities (ϵ) during smolder

Product	Emissivity					Calculated at 0.87 emissivity
	0.99	0.92	0.8	0.7	0.6	
O	559	556	603	641	666	567
B1	535	571	593	614	640	582
B2	545	568	590	617	652	579
B0	555	563	598	619	653	574
FC1	557	569	588	612	657	580
FC2	554	580	594	634	672	591
RTS	565	584	602	637	673	596
CRES	565	585	613	635	668	596
Commercial	570	582	605	640	665	593
Average	556	573	599	628	661	584
Range	35	29	25	30	33	29
Standard deviation	11	10	8	12	11	10

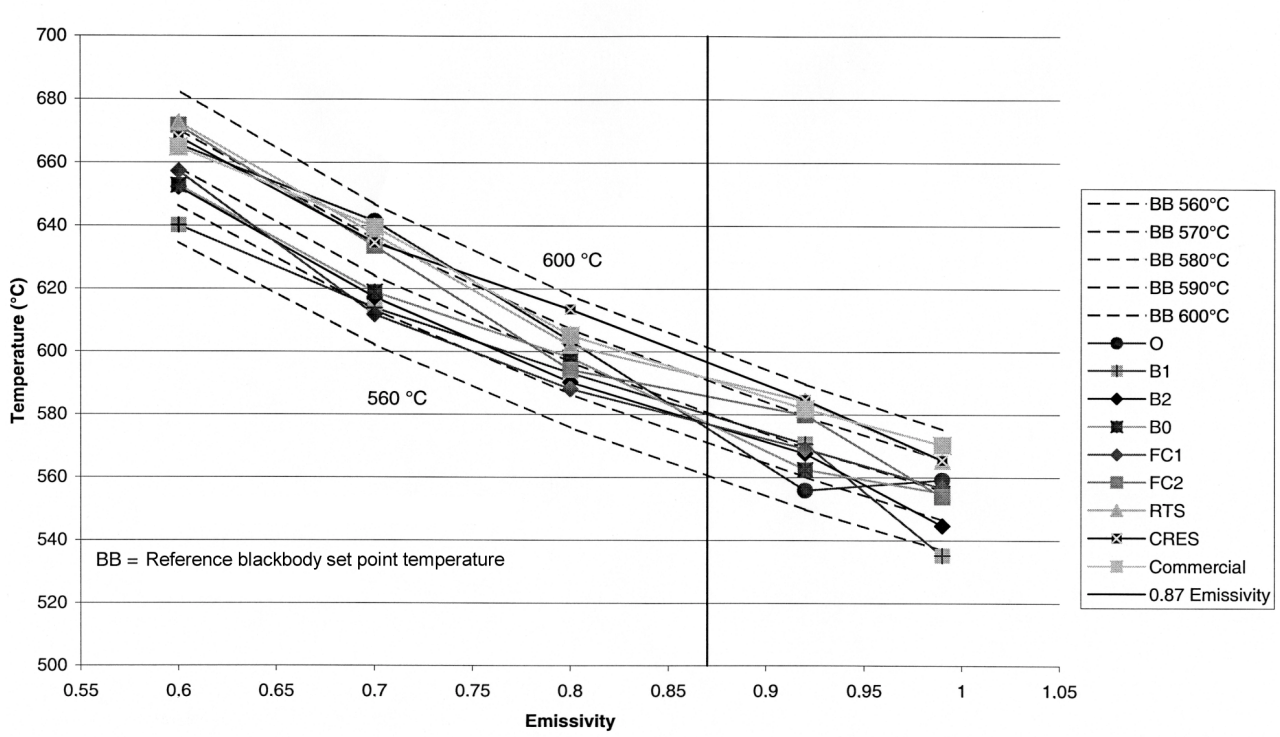

Figure 2. Emissivity/temperature study of single-tobacco-type cigarettes: Coal temperatures with blackbody set point measurements

it is important to know whether properties of tobacco types are different enough to cause differences in emissivity. The average maximum surface coal temperatures during smolder for the eight cigarettes containing single types of tobacco described in Table 1 and the average maximum surface coal temperature for a commercial cigarette were measured with a thermal imaging camera. Orientation of the tobacco rod was parallel to the camera lens. The cigarettes were run in triplicate. Temperature readings were collected every 2 sec for 30 sec. Data for all nine cigarettes are shown in Table 6. There was no discernible difference between the average maximum coal surface smolder temperature of the commercial blended cigarette and the cigarettes containing different tobacco types. LENDVAY and LASZLO (1,3) documented that the emittance of a cigarette coal during smolder closely approximated the emittance of a reference blackbody. During smolder for all cigarettes tested, the calculated average maximum surface coal temperature, with a camera emissivity of 0.87, which is the same value of the reference blackbody, was 584 ± 15 ˚C (Table 6). This average maximum surface smolder temperature is within the range observed by LENDVAY and LASZLO (3), 585–595 ˚C.

An analysis of variance was conducted on the average maximum surface coal temperatures, during smolder, for the eight single-tobacco-type cigarettes and a commercially available cigarette to compare the average temperature change with emissivity (Figure 2). A significant change in

Table 7. Peak smolder coal temperatures ˚C (thermocouple) for a series of filtered single-tobacco-type cigarettes

Product	OF	BF	FCF
Thermocouple temp.	713	774	752
	788	746	770
	726	747	716
	759	746	782
	736	705	684
		773	738
		786	732
		738	719
		767	683
		739	735
		741	793
		758	737
		783	
		697	
		773	
Average	744	751	737
Standard deviation	29	26	34

Table 8. Peak smolder temperatures (˚C) using thermal imaging for a series of filtered single-tobacco-type cigarettes

Product	OF	BF	FCF
Thermal imaging temp.	726	737	722
	709	750	734
	719	754	708
	746	757	735
	695	749	719
	739	755	734
	750	731	676
	728	756	747
	717	745	712
Average	725	748	721
Standard deviation	18	9	21

Table 9. Comparison of peak smolder coal temperatures (˚C) for two testing methodologies

Product	OF	BF	FCF
Thermocouple	744	751	737
Thermal imaging	725	748	721
% Difference	3	0	2

the slope would indicate that a sample could possess a different emissivity. This analysis showed no significant differences among the slopes fitted for the nine samples. However, the reference blackbody data showed that for set points 30 ˚C apart (similar to the range among the tested cigarettes), only small changes in the differences across emissivity levels (2–3 ˚C) were observed. With the variability in the cigarette data and the sensitivity limitations of the thermal imaging system, changes in the slopes caused by these kinds of differences would not be detected. These data suggest that there is no evidence to suspect that different tobaccos tested have different emissivities.

Thermocouple vs. thermal imaging experiments

It has been reported that thermocouples measure gas stream temperatures while thermography essentially measures solid-phase temperature (8). During a puff, these phases can have quite different temperatures near the surface of the cigarette coal, though they are very similar at the center. During smolder, the two reach quasi-equilibrium (9) so both methods of measurement should yield similar results.

Peak coal temperature measurements with thermocouples: The three filtered single-tobacco-type cigarettes described in Table 3 were prepared with thermocouples placed into the cigarettes in a manner similar to that of TOUEY and MUMPOWER (7). The cigarettes were puffed twice and then allowed to smolder. The peak smolder coal temperatures, measured with thermocouples, for flue-cured, burley, and Oriental cigarettes were 736, 751, and 744 ˚C, respectively (Table 7).

Peak coal temperature measurements with thermal imaging: Samples of the same three filtered cigarettes were measured with the thermal imaging camera. Cigarettes were positioned horizontally and viewed by the thermal imaging camera in a field coaxial (coal face on) to the camera body and perpendicular to the lens surface. The cigarettes were lit and allowed to smolder 30 mm. The cigarettes were then tapped to remove the ash before coal temperatures were measured every 2 sec for 30 sec. Experimental results were based on triplicate analyses. The peak coal temperatures obtained by thermal imaging for flue-cured, burley, and Oriental cigarettes were 721, 748, and 726 ˚C, respectively (Table 8). A comparison of the two data sets showed excellent correspondence, with a difference of less than 3% (Table 9).

TOUEY and MUMPOWER (7) noted that the type and diameter of thermocouples greatly affect the measurement of peak coal temperature during the puff. They found that as the diameter of the thermocouple decreased, its sensitivity to temperature change increased. The type "R" thermocouples they used were platinum (87%), rhodium (13%) wires of diameters between 0.025–0.1 mm. The type "E" thermocouples used in these experiments were stainless steel wires 0.25 mm in diameter. TOUEY and MUMPOWER (7) also reported peak coal temperatures during smolder between 805 and 866 ˚C for a 0.025 mm thermocouple. For thermocouples of 0.1 mm, the range in peak coal temperature measured was 737–789 ˚C. The peak smolder coal temperatures reported in the present experiments ranged from 683–788 ˚C. These results are expectedly lower than those observed by TOUEY and MUMPOWER (7) due to both the larger diameter and number of thermocouples employed in these experiments.

SUMMARY AND CONCLUSIONS

Average maximum smolder coal temperatures for unfiltered cigarettes made with different tobacco types and a commercial blend cigarette were determined and were found to be similar (584.4 ˚C ± 15 ˚C). If emissivity differences exist among the products tested, the variability in these data and the sensitivity limitations of the thermal imaging system preclude detection.

Comparing thermocouple measurements to thermal imaging measurements, data sets were very similar, varying by less than three percent. The peak smolder coal temperatures measured with thermocouples for filtered flue-cured, burley, and Oriental cigarettes were 736, 751, and 744 ˚C, respectively. These temperatures were very similar to the peak smolder coal temperatures obtained by thermal imaging (721, 748, and 726 ˚C, respectively). These results confirm that during smolder the gas-phase temperature inside the coal (as measured with the thermocouple) and the solid-phase temperatures beneath the ash (as measured with the camera) are in near thermal equilibrium. With proper calibration, a thermal imaging system is an excellent alternative to thermocouples for measuring cigarette coal temperatures.

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