Two New Methods for Measuring Performance of Underfired Broilers

Presented to the American Society of Gas Engineers, June 5th, 2012

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TWO NEW METHODS FOR MEASURING PERFORMANCE OF UNDERFIRED BROILERS

The measurement of performance of underfired (open-top) broilers has traditionally been done using thermocouple arrays and ASTM F1695 Standard Test Method for Performance of Underfired Broilers. This paper describes two new methods developed by Charbroil Research and Development to provide comparative assessment of energy efficiency and cooking effectiveness. Advantages and limitations of the new methods compared to existing procedures will be discussed and the paper will provide some assessment of repeatability and reproducibility as well as judgment as to the effectiveness of these tests in analyzing and differentiating product performance.

What do we want to know about the thermal performance of broilers?

- What is the heat output?
- How evenly do they heat?
- How efficiently do they heat?
- What is the effect on food?
- What are the combustion characteristics?

Current measurement methods

- *Heat output* is most often measured by TC array but the question is what is actually being measured? It is a specific thermal event relating to the heat transferred to the heat sink the TC is mounted on. That may or may not be well coupled to the heat output of the broiler.
- It is also possible to use calorimetric methods, which using the technique of Willie H Best at TEC, can be fairly simple involving the use of a closed can of water. However, this can only measure one point at a time and requires some close attention to get good manual measurements of time and temperature.

Current measurement methods

- It is possible to indirectly measure heat output to food by using the involved and complicated procedure of ASTM F1695. But this test method can in no way seem suitable for measuring a wide range of products in a limited amount of time with limited resources, since it requires elaborate food preparation and data analysis.
- A thermal camera can also be used to analyze surface temperatures and produce a good overall picture of temperature but cannot directly inform us about gas temperatures which are involved in convective heating.

Current measurement methods

- *Heat evenness* is normally measured by a TC array. The issues about TCs raised earlier are valid as well as the question of how dense to make the TC array and how or whether or not to change TC array geometry when moving from unit to unit.
- Evenness can also be evaluated by visual observation of food being cooked though it is hard to make a quantitative record of such events and results can be strongly effected by cooking technique.

Current measurement methods

- *Efficiency* can be measured by use of F1695 heavy and light load cooking tests. However, this a time consuming and difficult test to carry out on a single product, so using it for evaluation of a significant number of different products stretches the bounds of economic practicality.
- Efficiency could also be evaluated by comparing the heat output using a calorimetric technique to the heat input to the burner system based on gas flow rate or other energy measure. One of the new methods to be discussed does this using a different method of measuring heat output.

Current measurement methods

- *Food effect* is not covered by any truly standard technique, although academic food science has proposed and practices many such methods. A recent review of leading academic papers covering the effect of different cooking methods on different foods conducted for Charbroil by Research Triangle Institute uncovered 18 papers using 18 different techniques.

Current measurement methods

- *Combustion characteristics* are normally measured with gas analyzers of various types that give various types of useful results.
- For example excess air % and CO2 % provide a useful yardstick for comparing the efficiency of the burner system in producing hot gas. However, this may or may not be strongly correlated with the overall efficiency of the system in providing heat to the food being cooked.
- Conformance to regulatory standards, usually CO% , is normally established using these methods.

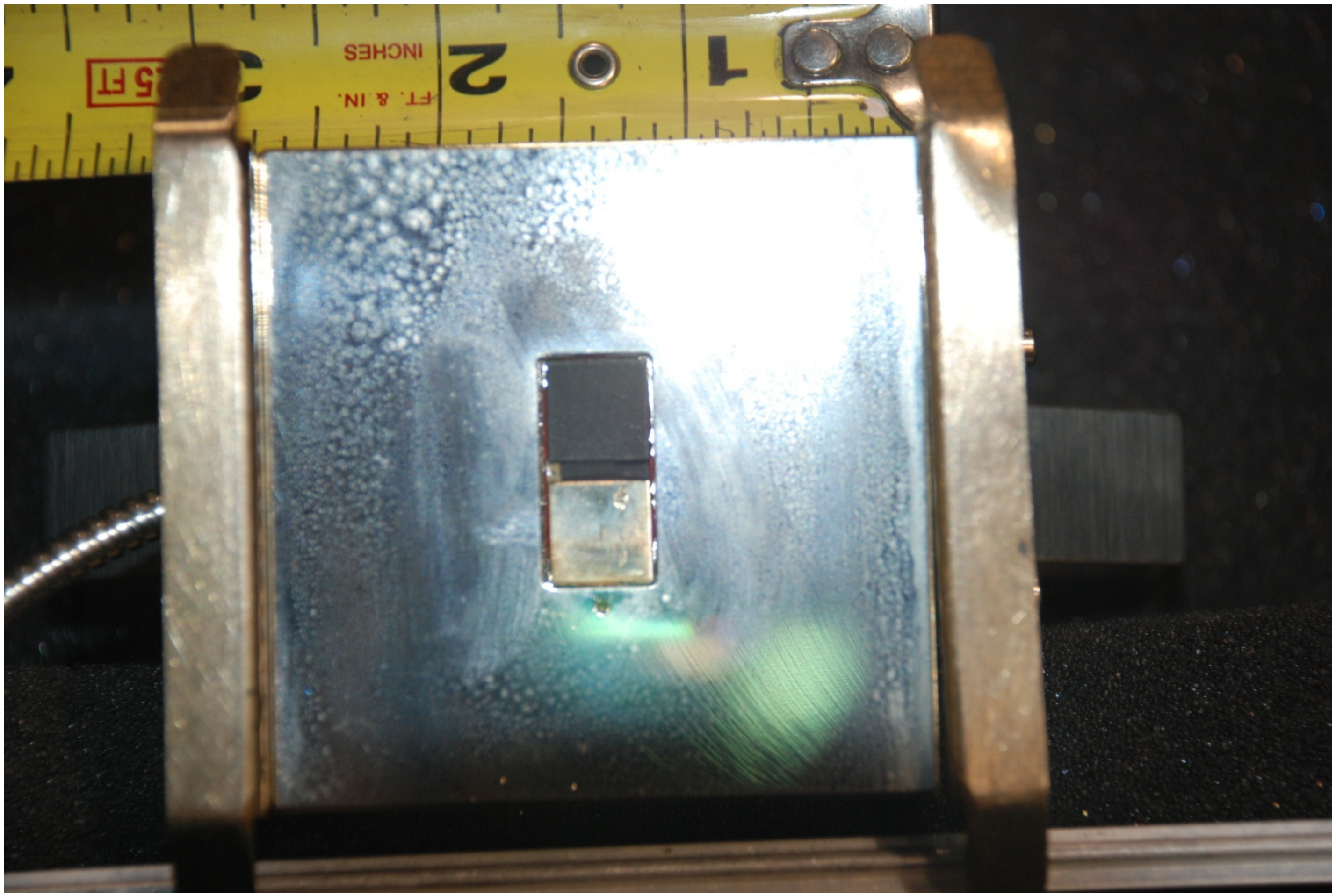
Desirable attributes of alternative methods

- There should be a clear physical meaning of the measured parameters that directly relates to the design of the product in question.
- Several characteristics of the system should ideally be measureable in the same test.
- The tests should be simple and straightforward to perform allowing testing of large numbers of samples with normal lab technician skill levels.
- The tests should be repeatable from test to test and reproducible from lab to lab

RC heat flux sensor - description

The radiant/convective heat flux sensor of the type RC01 manufactured by Hukseflux Thermal Sensors, Delft, The Netherlands, comprises two thin film thermopiles adjacently mounted in a block of nickel. Over one thermopile is a black window with an emissivity of around .83 and over the other is a gold window with an emissivity less then .05. Provision for water cooling is possible if sensor temperatures above 250C are expected to be attained during the course of the test run.

RC heat flux sensor – operating face



RC heat flux sensor – operating principle

By comparing the outputs of the two sensors, convective heat flux, measured by the gold windowed sensor, can be subtracted from total heat, measured by the black windowed sensor, to calculate the radiant heat flux. As the output of the sensors are not independent of temperature a correction factor needs to be calculated using an internal thermocouple that measures and outputs the temperature at the sensors. This is accomplished by programming in any standard DAS software.

RC heat flux sensor – measurement approach

Bearing in mind that we will be measuring and comparing radiant and convective heat and will not include conduction we were faced with the decision as to the measurement approach. We decided to measure the heat flux along a plane some finite distance above the food support element. That distance was ultimately chosen after a number of trials to be about 8mm above the food support element. We were attempting to get a close as possible to the support element without running the risk of contacting the food support element with the windows over the thermopiles.

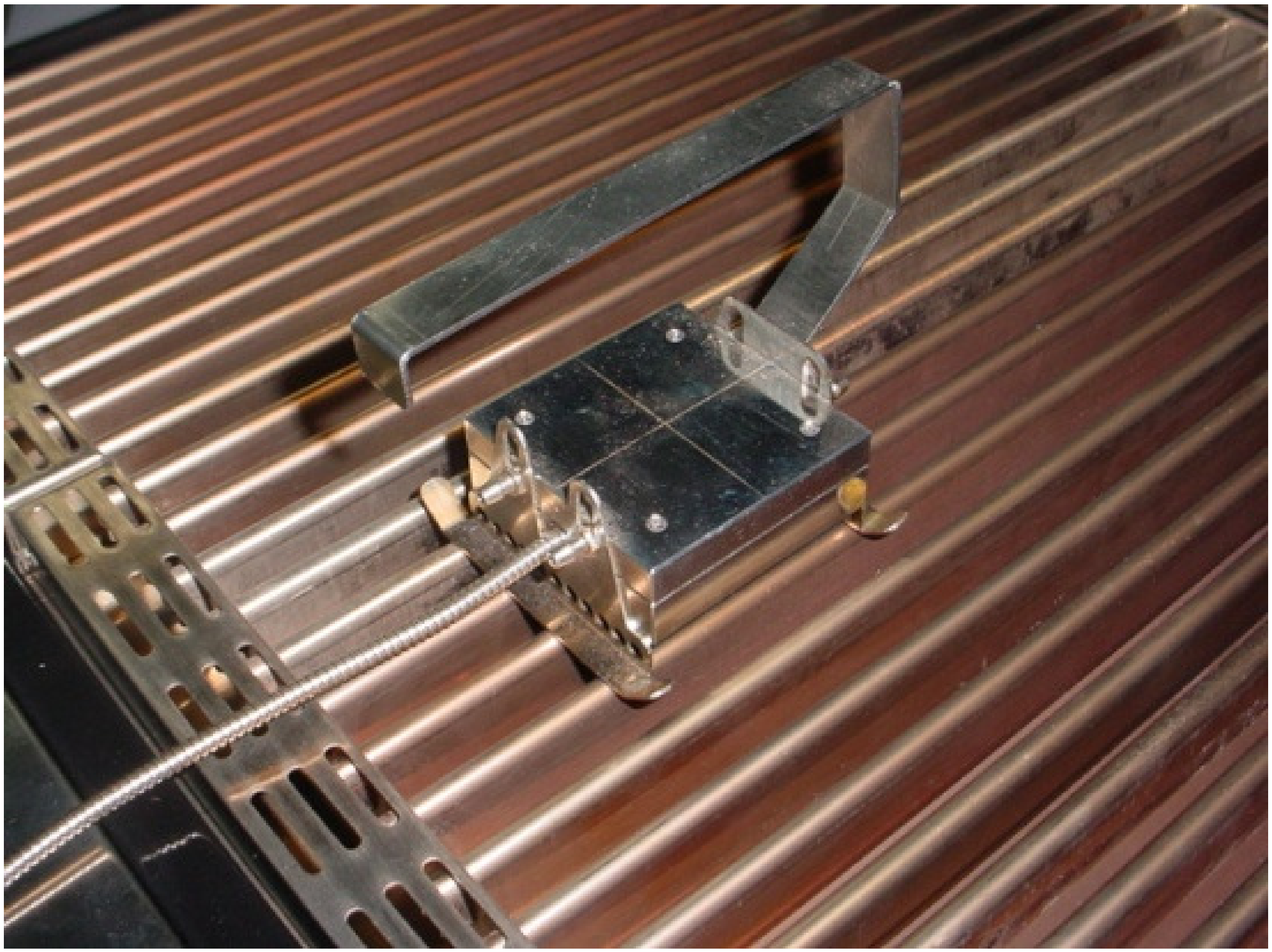
RC heat flux sensor – measurement approach

We understand that by ignoring conduction effects from the food support we seem to be not faithfully measuring the heat input to the food item. From a conceptual point of view we have established a control surface in a plane just above the food support, for practical reasons, and are treating this as the heat source to the food. In any case, we believe, as we shall see, that a great deal of information can be gained from measuring the radiant and convective heat at that surface. In many outdoor applications, cooking by conduction is not desired and food contact area is intentionally minimized.

RC heat flux sensor – measurement approach

Given the nature of open top broilers, especially those designed for outdoor use, it was apparent that measurement at a single point could be unrevealing or misleading. We decided to use a scanning technique with continuous timed *scans* or stopping at multiple *points* for measured lengths of time. The continuous scan technique is quicker to develop data but the point by point method gives better diagnostic precision in some cases. We have used both methods and for initial characterization they give equivalent results. Repeated trials on the same product show around a 2% difference. The coverage of the scanned path on the cooking area is a matter of judgment based on experience.

RC heat flux sensor – on cooking surface



RC heat flux sensor – sample data, single point

time	Black	Gold	Air TC	Sensor TC	Measured Black Flux	Measured Gold Flux	TD corr	Measured Total Flux	Measured Conv Flux		Actual Rad Flux	Actual Total Flux	% Rad
0	0.021659	0.009656	273.1783	32.72493	10.883687	5.4864054	0.992365	10.9674232	5.5286162		6.55278	12.0814	54.24%
1	0.023297	0.008896	241.8767	32.91691	11.707148	5.0547035	0.99225	11.7985886	5.0941842		8.077596	13.17178	61.33%
2	0.023112	0.012951	299.4355	33.26171	11.613879	7.3587575	0.992043	11.7070321	7.417781		5.167772	12.58555	41.06%
3	0.01925	0.006839	236	33.24619	9.6735278	3.885654	0.992052	9.75102616	3.9167835		7.029208	10.94599	64.22%
4	0.018992	0.007417	227.9578	33.23674	9.5438998	4.2144519	0.992058	9.62030475	4.2481912		6.472426	10.72062	60.37%
5	0.019729	0.008225	271.058	33.4874	9.914189	4.6735603	0.991908	9.99507353	4.7116894		6.365523	11.07721	57.47%
6	0.022738	0.010507	251.1417	33.69311	11.426212	5.9701116	0.991784	11.5208662	6.0195676		6.628071	12.64764	52.41%
7	0.020481	0.010399	267.2021	33.80899	10.291857	5.9086591	0.991715	10.3778412	5.9580237		5.325081	11.28311	47.20%
8	0.020572	0.007707	231.7896	33.90461	10.337926	4.3787231	0.991657	10.4248983	4.4155611		7.240165	11.65573	62.12%
9	0.018304	0.005784	239.2224	33.91536	9.1981508	3.2863617	0.991651	9.27559474	3.3140312		7.182607	10.49664	68.43%
10	0.01937	0.007188	237.4707	34.01521	9.7336744	4.0839712	0.991591	9.81622021	4.1186051		6.864597	10.9832	62.50%
11	0.020303	0.009244	245.8322	34.19854	10.202577	5.2525101	0.991481	10.2902408	5.2976413		6.01518	11.31282	53.17%
12	0.018896	0.006714	225.9198	34.22668	9.4954215	3.8145832	0.991464	9.57717226	3.8474249		6.90331	10.75073	64.21%
13	0.020937	0.008214	219.4729	34.36517	10.521227	4.6670918	0.991381	10.6126988	4.7076677		7.114495	11.82216	60.18%
14	0.016643	0.004905	217.1083	34.40848	8.3635491	2.7871643	0.991355	8.43648323	2.8114697		6.777125	9.588594	70.68%
15	0.019839	0.006787	228.4653	34.53397	9.9692924	3.8561192	0.99128	10.0569932	3.8900418		7.430062	11.3201	65.64%
16	0.021567	0.007468	212.8601	34.7614	10.837617	4.2433909	0.991143	10.9344621	4.2813097		8.015846	12.29716	65.18%
17	0.01662	0.004681	237.6134	34.67125	8.3515804	2.6596625	0.991197	8.42575022	2.6832828		6.918635	9.601918	72.05%
18	0.016316	0.0045	207.507	34.71397	8.1989175	2.5570993	0.991172	8.27194539	2.5798755		6.857916	9.437791	72.66%
19	0.015249	0.003328	167.839	34.66945	7.6630176	1.890822	0.991198	7.73106387	1.9076122		7.016207	8.923819	78.62%
20	0.015137	0.003638	156.9842	34.59344	7.6063338	2.0671795	0.991244	7.67352362	2.0854397		6.732631	8.818071	76.35%
21	0.016314	0.003397	165.0417	34.76535	8.1977887	1.9300598	0.991141	8.27106377	1.9473115		7.618979	9.56629	79.64%
22	0.018276	0.004844	172.2132	34.92427	9.1839226	2.7520971	0.991045	9.26690365	2.7769636		7.819205	10.59617	73.79%
23	0.022587	0.01219	274.0493	35.33354	11.350182	6.9261195	0.9908	11.4555744	6.9904324		5.379689	12.37012	43.49%
24	0.020183	0.009472	258.0014	35.52029	10.142205	5.3818846	0.990688	10.2375386	5.4324727		5.789236	11.22171	51.59%
25	0.024055	0.009606	253.6548	35.63275	12.087826	5.4578069	0.99062	12.2022788	5.509484		8.063608	13.57309	59.41%
26	0.022763	0.011888	291.4859	36.12014	11.438934	6.7544434	0.990328	11.5506533	6.820411		5.699087	12.5195	45.52%
27	0.0228	0.01117	306.0527	36.2296	11.457151	6.3466591	0.990262	11.569815	6.409069		6.217766	12.62684	49.24%
28	0.025697	0.017794	322.397	36.65704	12.913017	10.110089	0.990006	13.0433752	10.212151		3.411113	13.62326	25.04%
29	0.020111	0.008639	272.6307	36.72329	10.105846	4.9086468	0.989966	10.2082754	4.9583992		6.325152	11.28355	56.06%
30	0.024767	0.012935	329.2495	36.93299	12.445619	7.3493099	0.98984	12.573362	7.4247437		6.203155	13.6279	45.52%
										avg	6.619814	11.37195	59.33%
	mV	mV	C	C <250	kW/m2	kW/m2		kW/m2	kW/m2		kW/m2	kW/m2	
								temperature corrected					

RC heat flux sensor – measurement approach

There remains the question of what thermal conditions are to be evaluated. In commercial applications of open top broilers one might assume a fairly steady state of continuous operation at a fixed input rate for hours at a time. However, in residential use the situation is more complex with varying levels of gas flow likely and different intervals of the normally provided lid being open and shut as well as widely varying cooking loads.

RC heat flux sensor – test procedure

Our decision was to carry out the following cycle:

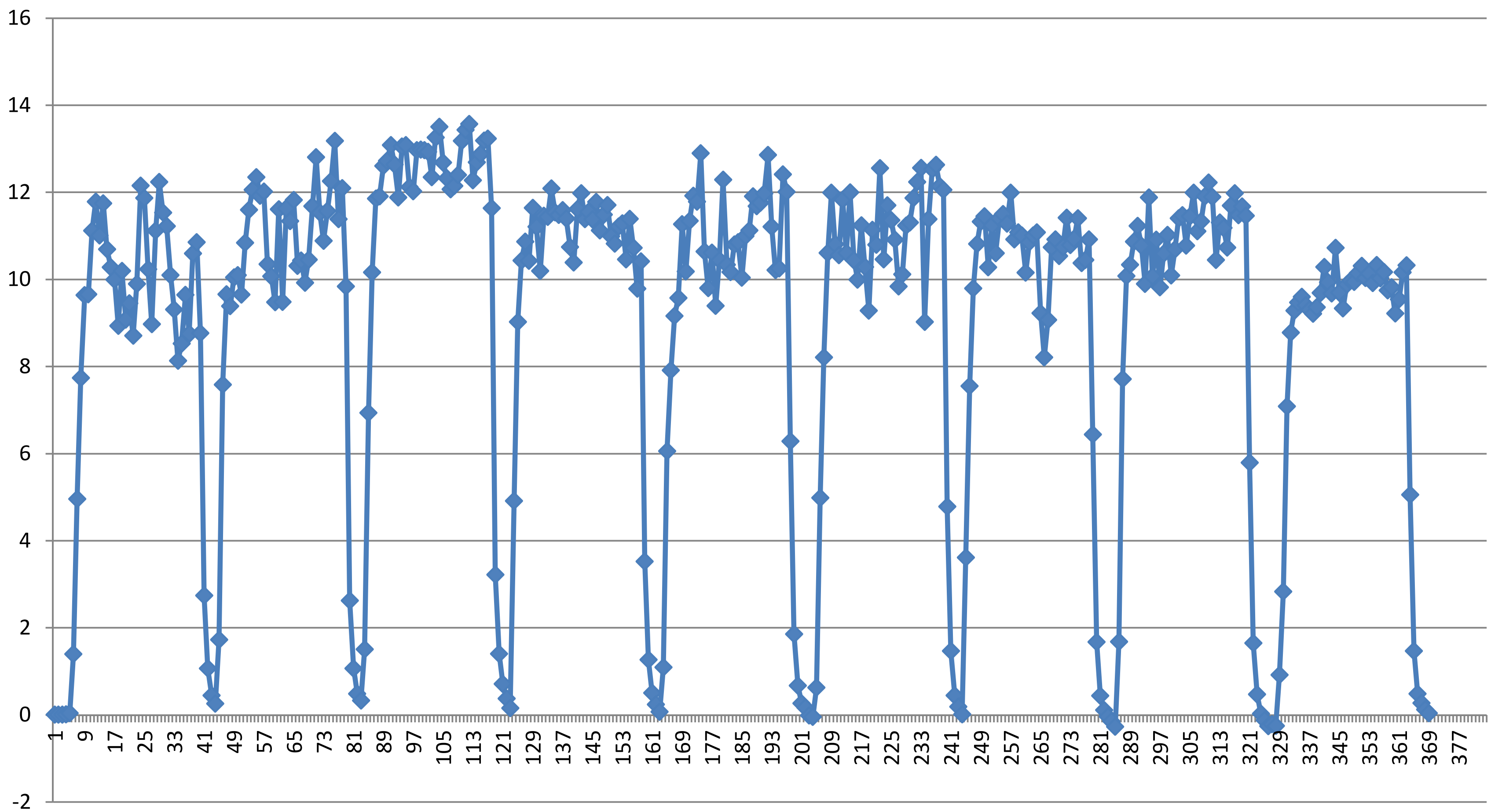
1. *Warm up the grill for 30min lid closed on lowest heat setting insuring thermal stability on most typical grills.*
2. *Open the lid, leave the unit on low, wait 5min, then carry out the scanning measurement*
3. *Close the lid turn to highest setting and run for 30min.*
4. *Open the lid, leave the unit on high, wait 5min, then carry out the scanning measurement*

Clearly other test procedures could be carried out and were evaluated and arguments made for and against each. We believe this particular approach accomplishes the task at hand in the minimum time and covers a wide enough range of operating conditions.

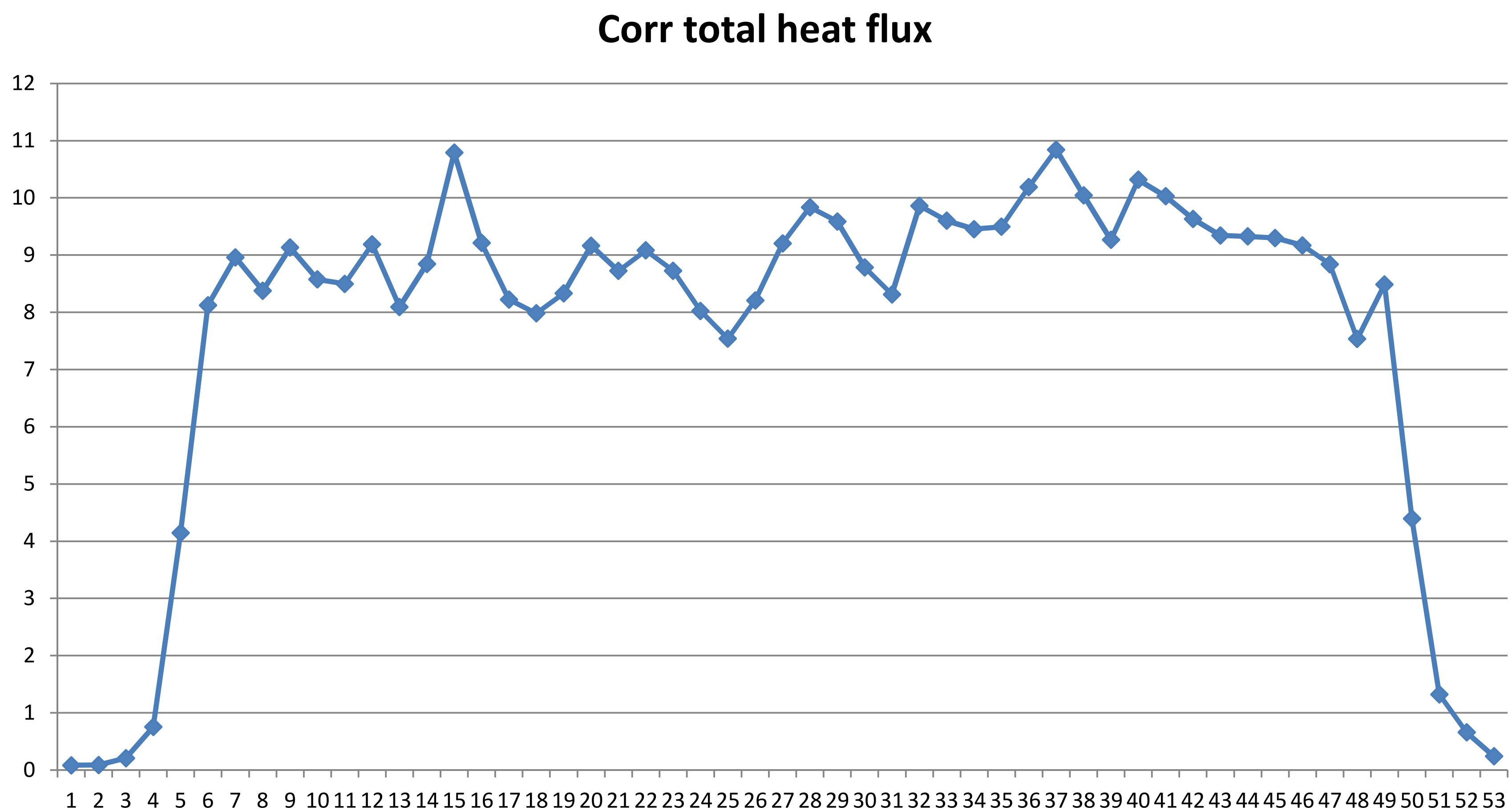
RC heat flux sensor – output quantities

The first result obtained is *total heat flux* in units of kW/m2. Since the flux is measured at each point an average of all points can be used as a measurement of the heat flux for the entire surface, which immediately gives the output power at the measurement plane in kW for the whole device. The high and low setting measurements can be related to the actual range of heat delivered to the food

RC heat flux sensor – example total heat flux point method single lateral line – kW/m2 vs time (sec)



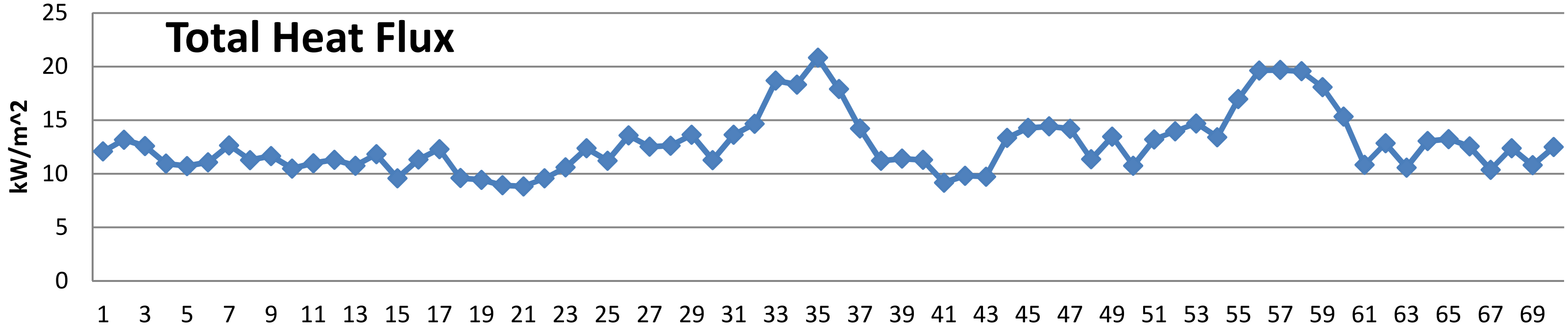
RC heat flux sensor – example total heat flux scan method single lateral line – kW/m2 vs. time(sec)

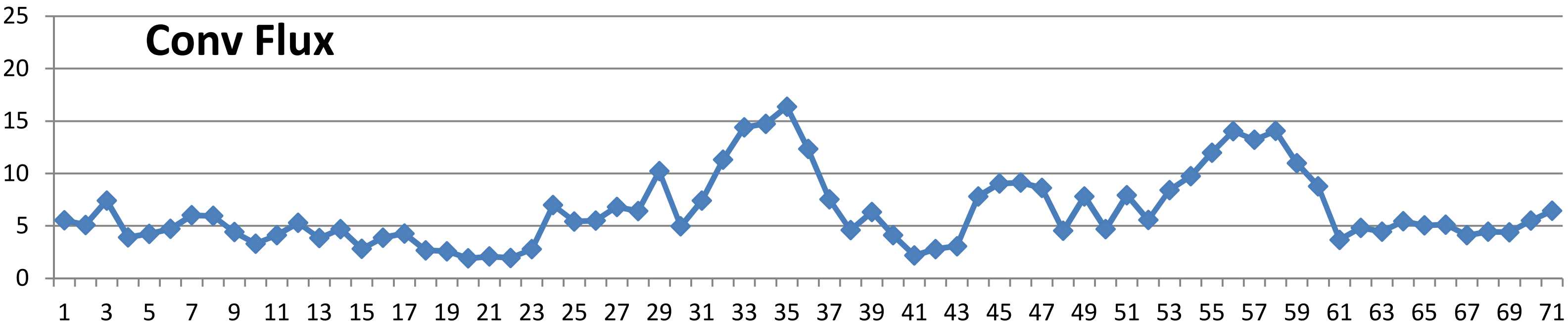


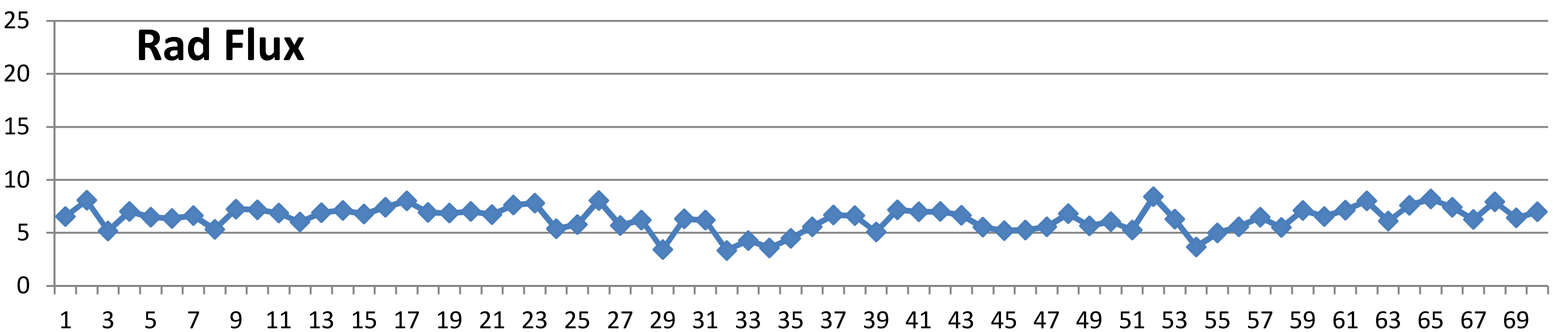
RC heat flux sensor – output quantities

The second measurement available is the distribution of *heat flux over time.* It is immediately apparent upon use of the heat flux sensor that variation in reading from one second to the next at the same location is quite considerable, normally due to convective flow instability, which can be also seen in CFD modeling of an open grate broiler. By comparison the radiative component of the heat flux has significantly less measured fluctuation as would be expected from a physical point of view.

RC heat flux sensor – heat flux over time, single point measurement – kW/m2 vs. time(sec)



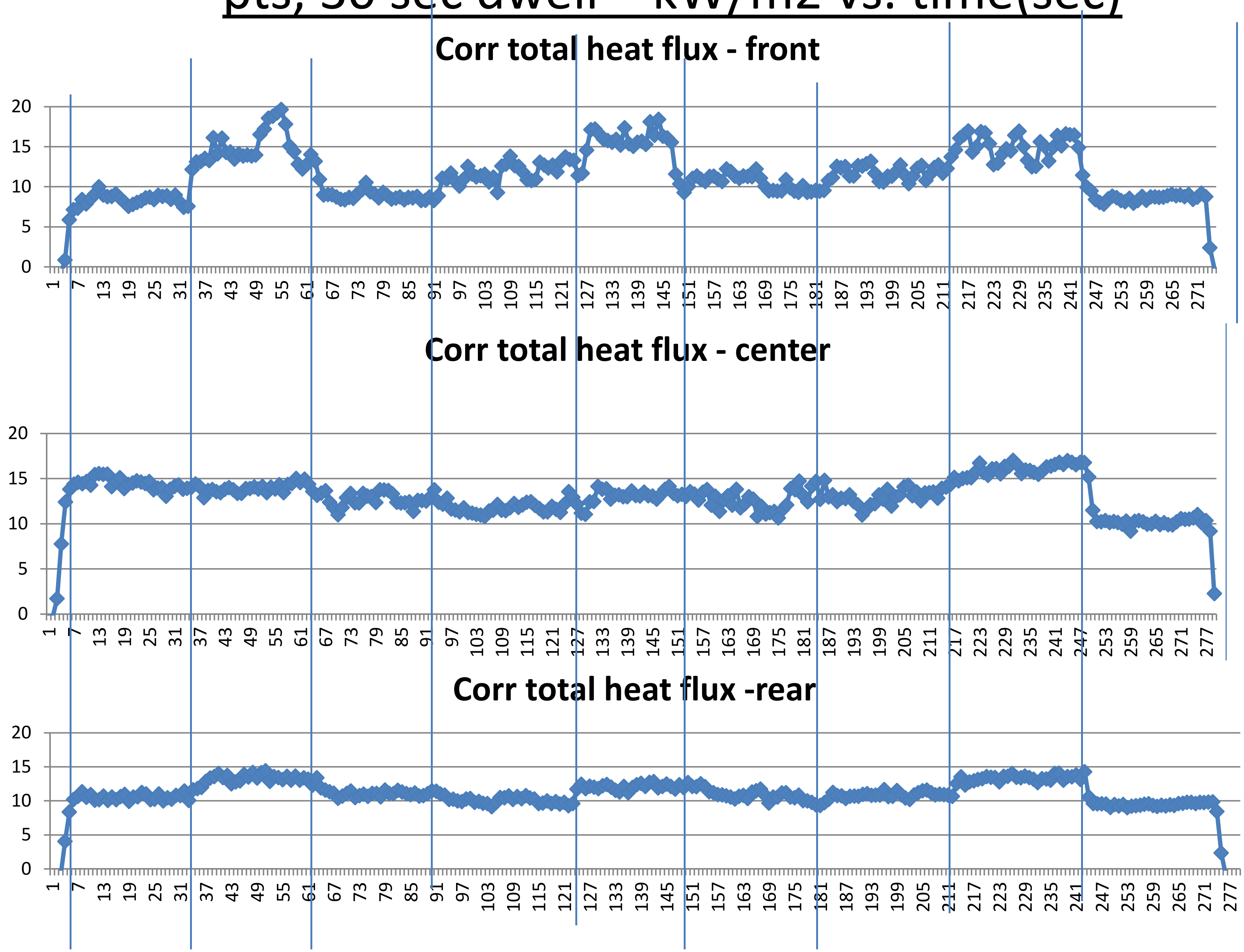




RC heat flux sensor – output quantities

The next measureable available is the *heat flux over space* which would normally be termed the heat distribution. The scanning technique, whether continuous or point by point, will produce a map of the total heat flux and due to the capabilities of the instrument, separate maps of convective and radiative heat flux. Different products tested will show different levels of variation that can be characterized using statistical measures such as standard deviation or coefficient of variation. Comparison of these results to TC array results shows broad agreement but with the added information as to radiant and convective contributions.

RC heat flux sensor – example heat flux over space, 27 pts, 30 sec dwell – kW/m2 vs. time(sec)

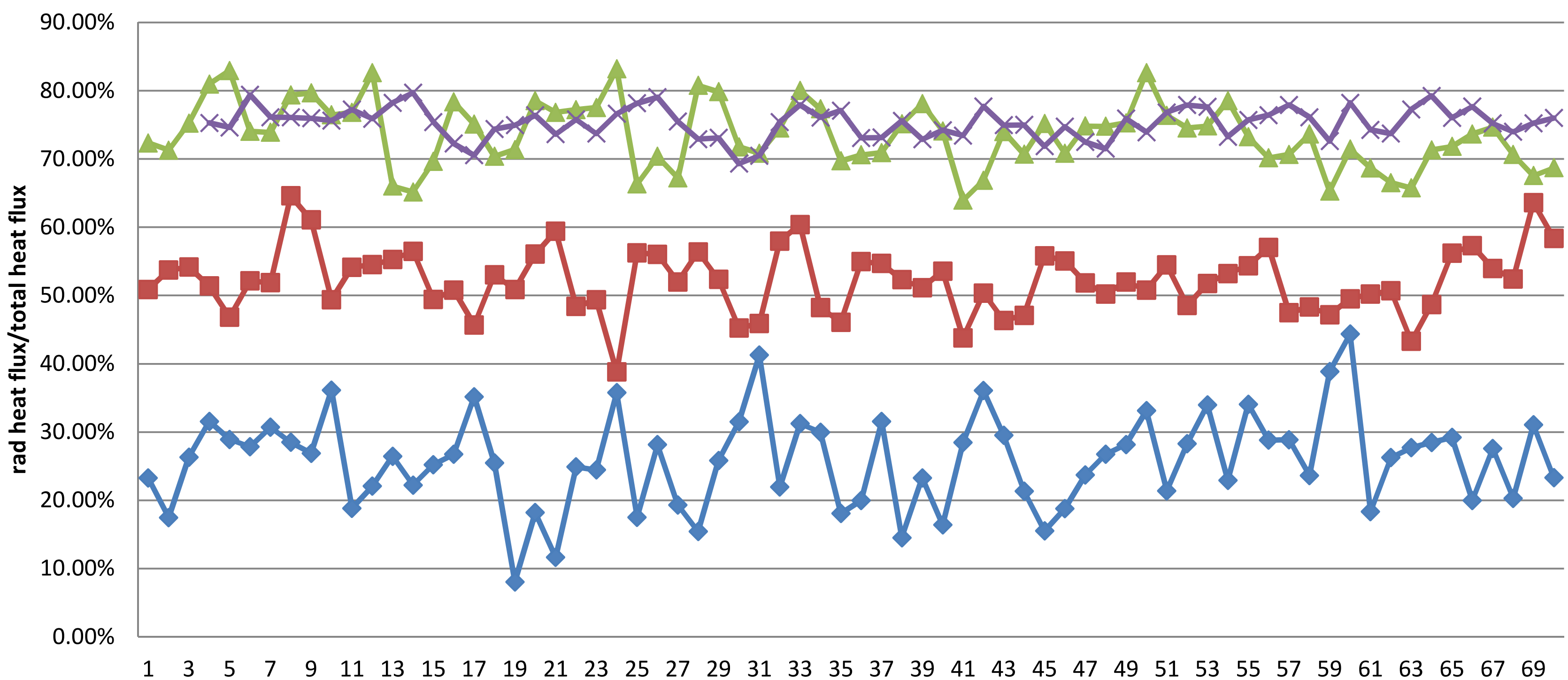


RC heat flux sensor – output quantities

The fourth output measureable is the *ratio of radiant to convective heat*. This is a direct result of the measurement of total heat flux and convective heat flux with their difference corresponding to the radiant heat flux. The ratio produced facilitates understanding of the heat production and distribution characteristics of the cooking system and characterizes the cooking effect on the food based on the balance of radiant to convective heating.

RC heat flux sensor – example ratio of radiant to convective heat flux

% IR , center of grill, four grills, one run at centroid of grate area

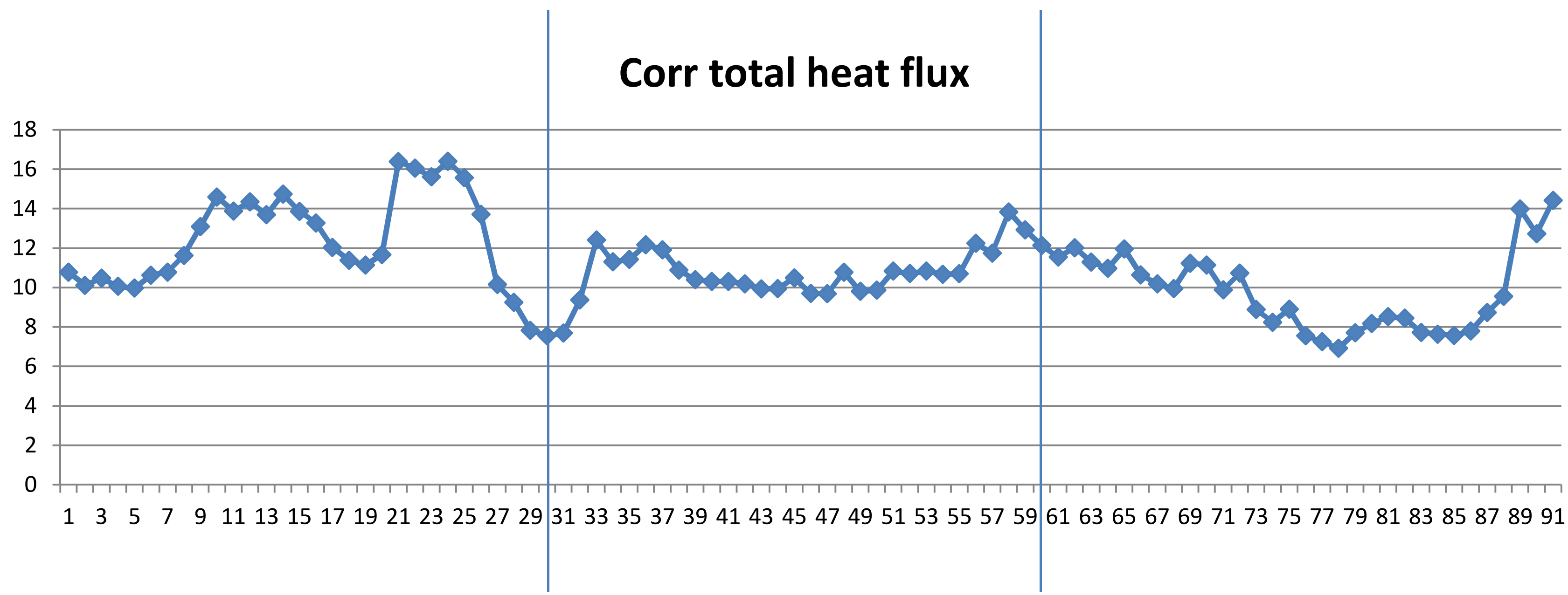


RC heat flux sensor – output quantities

The final output measureable is a type of comparative *efficiency* measure. This is computed by taking the total averaged heat flux and dividing it by the ratio of input power (derived from gas heating values, solid fuel heating values, or electrical power consumption) to total heated area of the appliance. Note this is not an energy balance calculation and only compares heat flux across the control surface plane discussed above to the maximum potential heat generation based on input energy. The number computed in this way is normally well below 50%.

RC heat flux sensor – example of efficiency

	38,861 BTU/hr High rate				
	1.5 minute flux test				
	30 seconds per section		heated area	471.75	
	Front L to R	input	BTU/hr/in^2	82.376	
	Center R to	input	kw/m^2	37.400	
	Rear L to R				
		average total flux	cf var flux	therm eff	
		10.97	20.41%	29.32%	
		kW/m2			

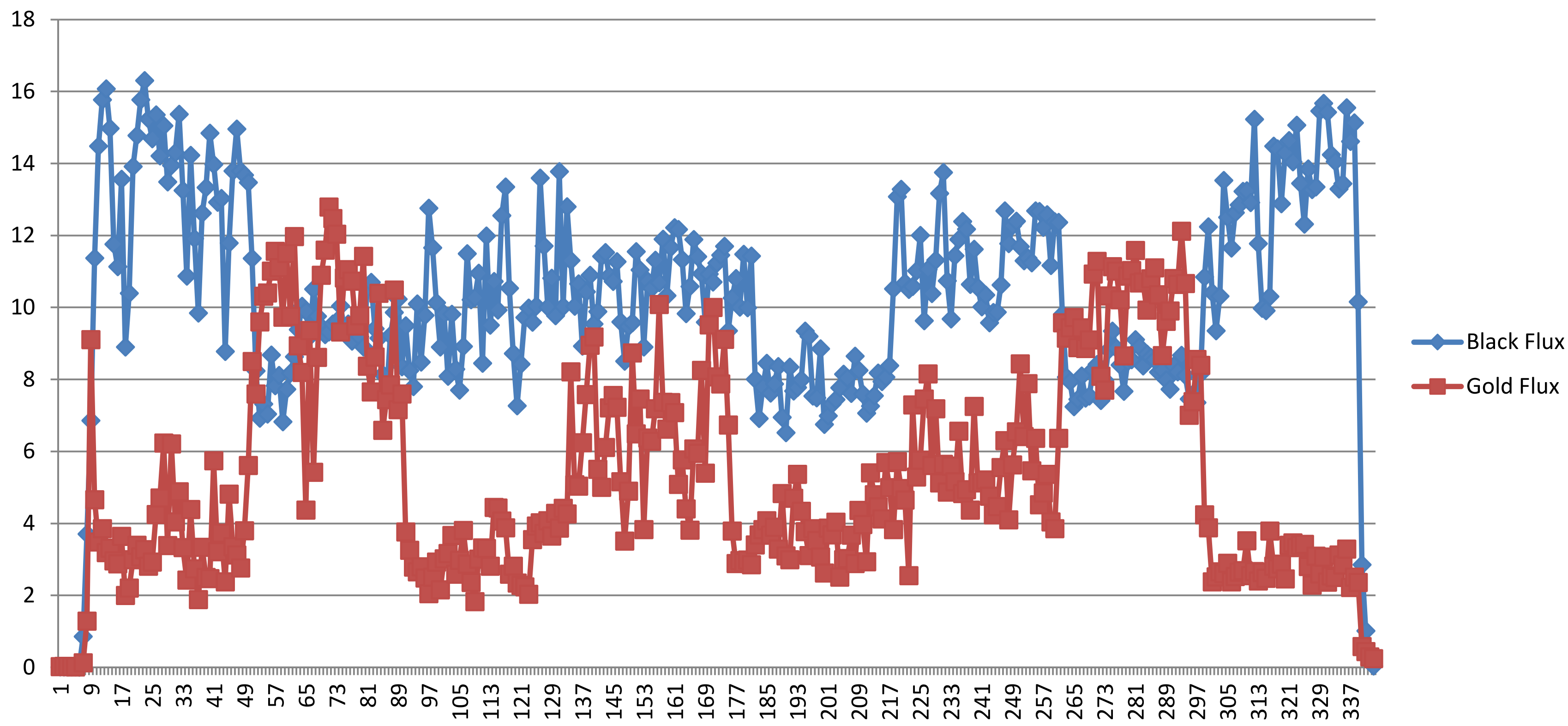


RC heat flux sensor – characteristics and limitations

One significant operating characteristic of the RC01 is that since the two windowed heat flux sensors occupy a finite area, a localized region of relatively high vertical velocity hot gas can create a higher heat flux measurement at the gold windowed sensor than at the black windowed sensor, thereby creating a physically meaningless negative radiant heat flux. Reorientation of the measurement block by 90 deg at the same point usually clarifies the situation at hand. Another way to look at this as being a product of the scale of the sensor separation compared to the scale of the geometry below the control surface.

RC heat flux sensor – characteristics and limitations

Illustration of effect of localized convective jet



RC heat flux sensor – characteristics and limitations

Another issue is that tracking changes in heat flux over long times such as a 30 min thermal stability period at high rate may run the sensor temperature up to the point which would require the use of water cooling.

A final issue relating to the heat flux sensor is that it is relatively expensive, though not unreasonably so given the material used for the heat sink and windows and the use of dual thermopiles. However this is treatable as a capital expense to be justified by the labor cost over a large number of tests.

RC heat flux sensor – repeatability and reproducibility

Our repeatability studies have been relatively sparse but the available data shows a coefficient of variation of up to 3.3% for heat flux values on repeated tests with the same sensor and same unit.

Testing with two sensors on the same unit was conducted when we purchased the second RC01 heat flux sensor and we found a difference of 2.4% between average heat flux values

RC heat flux sensor – summary

The conclusion of this presentation is that the Hukseflux RC01 heat flux sensor, or some similar device, can be used to develop and analyze a meaningful amount of useful information about the performance of underfired broilers while using a quite simple and straightforward test procedure with clear physical significance. In particular, comparisons of a considerable number of different configurations of products can be done in a reasonable period of time without extensive post test data reduction and analysis.

RC heat flux sensor – summary

One thing that is suggested by the success of the RC heat flux sensor is that the technique of using two targets, one that is highly absorptive of IR radiation and one that is highly reflective of IR radiation, could be extended as a technique to evaluate the relative balance of radiant and convective heat. We plan to explore this in the near future. Of course the simplicity of the direct output of heat flux from the RC01 will continue to weigh in its favor.

Quantitative cooking test method - introduction

Although the heat flux sensor described above offers a means of measurement for heat flux, heat distribution over time and space, radiant to convective heat balance and relative thermal efficiency, it does not offer any real insight as to food effects. We then decided to see what insights we could gain from instrumented food testing despite the daunting nature of such a task.

Quantitative cooking test method - introduction

Our first step was to research how the food science community was characterizing food effects as a function of cooking system. A recent review of several hundred academic papers conducted for Charbroil by Research Triangle Institute found the 18 most prominent papers to be using 18 different techniques. There did not appear to be a single generally accepted standard method of assessing food effects of different cooking systems, leaving us with little alternative to developing our own method.

Quantitative cooking test method - development

Our next step was to contact a respected independent testing agency with experience with gas fired appliances and work out some method that could allow us to compare different types of cooking systems. Our initial goal was to measure some criteria of "juiciness" from weight loss measurements before and after cooking. We wanted to use some type of meat product that could be considered standard enough to be replicable.

Quantitative cooking test method - development

We consulted with a professional butcher and after some discussion and consideration, came to the conclusion that the most consistent meat product we could use were pork loins cut in 1 “ slices cross ways to the direction of the muscle fiber. We then decided to cut these into 2” by 2” squares to form rectangular cubes. Initial tests were encouraging showing significant differences in weight loss depending on cook time and other parameters. Next we needed to define heat levels, cooking conditions and cycles, location on the cooking surface, and other similar variables. The following procedure was the resultant of these considerations.

Quantitative cooking test method - development

Test procedure was as follows: 2” x 2” x 1” pork loin squares at room temperature (72F +/- 5F) were cooked one at a time at four locations (quadrant centers) on each grill. After a 15 min warm up period with the grill on high with the lid closed the lid was opened for 5 min. Cooking was started with the lid closed for 4.5 min then the lid was opened, the meat flipped, and cooking continued until 160F internal temp was reached. The meat was then weighed and compared to the precooked weight. 5 trials were made at each of the four positions.

Quantitative cooking test method - development

The cooking cycle may seem arbitrary but was an attempt to fairly simply replicate a likely use pattern of cooking with gas grills where the lid is sometimes open and sometimes closed. Arguments that could be made about times and conditions would replicate internal discussions about the same, which were further complicated by the fact that we chose four grills with quite different though similarly sized (420 to 480 in2) cooking systems.

Quantitative cooking test method – weight loss

Tested with the above method we found weight loss of four different grills A, B, C, and D to be averaged at 19.84%, 20.15%, 23.95%, and 24.82%. Given that the maximum weight loss established by a 2 hour bake out was 56.40%, the question is whether the maximum 25% difference in weight loss measurement is significant. Statistically speaking, the standard deviations of the averaged data were between 1.09 and 1.65 indicating a difference of 1% in weight loss is not likely to be significant but a difference around 5% is likely to be significant. The question of sensory perception of these differences was not addressed in our work.

Quantitative cooking test method – evenness

During our preliminary work qualifying the procedure described we realized that we had significant variations in the time required to cook to 160F at the different quadrant locations on the various grills and therefore we could assess evenness of cooking by comparison of variation of cooking time at the four locations. This just required some work going through the data and the results were as follows:

Quantitative cooking test method – evenness results based on cooking times

	Quadrant 1	Quadrant 2	Quadrant 3	Quadrant 4	range	average	std dev	cf var
A	**556**	**556**	**517**	**526**	**39**	**538.8**	**20.3**	**3.8%**
B	**534**	**479**	**486**	**485**	**55**	**496.0**	**25.5**	**5.1%**
C	**897**	**908**	**783**	**752**	**156**	**835.0**	**79.1**	**9.5%**
D	**2651**	**2093**	**1630**	**1802**	**1021**	**2044.0**	**447.5**	**21.9%**

cooking time in seconds, average of five trials

Coefficients of variation of cooking time are similar to cf var of temperatures or heat flux

Quantitative cooking test method – gas consumption

If the grills being tested are run off calibrated wall meters and manometers the gas consumption can be measured during the course of the cooking activity and the rate multiplied by the cooking time and the results compared in terms of BTUs consumed. Below is a chart of results from one such comparison, allowing a relative evaluation of actual cooking efficiency.

A	B	C	D
3,552	**4,380**	**8,559**	**25,448**

Quantitative cooking test method – gas consumption

A point that might be missed in the previous slide is that the rate found is based on the BTUs being used during the cooking of one piece of meat at one quadrant centroid averaged for cooking in four places five times. Is this the same as cooking four pieces of meat at once, or eight or sixteen? Probably not since it is possible to suppose, following the rationale of ASTM F1695, that different results will be found in light load and heavy load cooking. However, will this difference make a difference in system comparisons? We think not but have not verified that belief.

TWO NEW METHODS FOR MEASURING PERFORMANCE OF UNDERFIRED BROILERS

We have reported on two new methods for measuring performance of these products. With hundreds of tests done, we feel like we understand the repeatability of the *heat flux sensor* technique. A true assessment of reproducibility will develop when other labs begin to use this or similar instruments. The *quantitative food test* is at an earlier stage of development and will be more fully understood with further testing at different labs which Charbroil will undertake to do.

Acknowledgements

I would like to thank:

- Kees-Jan van der Bos and Robert Dolce of Hukseflux Thermal Sensors and Hukseflux USA for helping us understand the use and functionality of the RC01
- Nancy Wilson of OnSpeX-CSA International for her help and advice in formulating and executing quantitative food cooking tests
- Jim Jollay and Dean Tsagaris of Charbroil for validating and running hundreds of heat flux tests
- Mallik Ahmed and Sleiman Abdallah of Charbroil and Eric Johnson of Atlantic Consulting for their review and comment of this material.