A STUDY ON ASH PARTICLE DISTRIBUTION CHARACTERISITICS OF CANDLE FILTER SURFACE REGENERATION AT ROOM TEMPERATURE

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Abstract

Ceramic barrier filtration is a leading technology employed in hot gas filtration. Hot gases loaded with ash particle flow through the ceramic candle filters and deposit ash on their outer surface. The deposited ash is periodically removed using back pulse cleaning jet, known as surface regeneration. The cleaning done by this technique still leaves some residual ash on the filter surface, which over a period of time sinters, forms a solid cake and leads to mechanical failure of the candle filter.

A room temperature testing facility (RTTF) was built to gain more insight into the surface regeneration process before testing commenced at high temperature. RTTF was instrumented to obtain pressure histories during the surface regeneration process and a high-resolution high-speed imaging system was integrated in order to obtain pictures of the surface regeneration process. The objective of this research has been to utilize the RTTF to study the surface regeneration process at the convenience of room temperature conditions.

The face velocity of the fluidized gas, the regeneration pressure of the back pulse and the time to build up ash on the surface of the candle filter were identified as the important parameters to be studied. Two types of ceramic candle filters were used in the study. Each candle filter was subjected to several cycles of ash build-up followed by a thorough study of the surface regeneration process at different parametric conditions. The pressure histories in the chamber and filter system during build-up and regeneration were then analyzed. The size distribution and movement of the ash particles during the surface regeneration process was studied. Effect of each of the parameters on the performance of the regeneration process is presented. A comparative study between the two candle filters with different characteristics is presented.

Introduction

Ceramic candle filters have the potential to become the choice for hot gas filtration due to their ability to withstand attack by aggressive gases at high temperatures. Ceramic candle filters are used to clean the hot gaseous products of coal combustion or gasification. The ash from these processes is deposited on the outer surfaces of the filters until the resulting pressure drop reaches a specified value. A short high-pressure pulse of gas then enters the inside of the filter and flows out through the filter wall, removing the ash layer of the surface. This cleaning process is referred to as surface regeneration, and the high-pressure pulse of gas is referred to as the back pulse or the regeneration pulse.

The room temperature test facility that was employed in this study is described in references [1-3].

Background

The goal of surface regeneration is to reduce the pressure drop across the filter by removing the ash layer. Theoretically, the ash layer should detach from the filter surface when the failure strength within the ash layer is exceeded. The ideal surface regeneration should remove all the deposited ash from the filter surface. However, in practice, patches of ash and a residual layer of ash may remain on the filter surface. The residual ash layer may grow with each regeneration process and this has been postulated to lead to the mechanical failure of candle filters. There were three types of surface regeneration processes observed in this study. A thin ash regeneration is defined as one where the ash layer appears to explode off the filter surface during regeneration initiated by horizontal cracks. A thick ash layer is defined as an ash layer where vertical cracks appear on the ash layer's surface and then large chunks of ash fall away from the filter surface during regeneration. The third, partial thick-thin type of regeneration is one where vertical cracks appear on the filter surface like the thick ash regeneration, but ash layer soon disintegrates like in the thin ash regeneration.

The conditions necessary for the efficient removal of the ash layer during surface regeneration have not been completely established. The surface regeneration process is affected by many variables. The objective of this study was to investigate the surface regeneration process from cycle-to-cycle in a continuous test and to investigate the distribution of particles about the filter surface just after regeneration. The variables investigated in this study were 1) magnitude of the regeneration pressure, 2) facial velocity on the filter surface, 3) cycle frequency (or filtration period), and 4) filter wall permeability characteristics. Tests were conducted at a selected set of conditions, including a surface regeneration frequency, until the results showed repeatability or the surface regeneration process failed to continue removing the ash from the surface.

Experimental Program

Each test consisted of a selected set of independent variables and the test was run over as many cycles as were required to reach conclusions about the performance of the system. A set of independent variables, referred to as "base conditions", was selected to serve as a reference condition. These conditions were: 95 psig regeneration pressure, 5cm/s face velocity, and 20 min. cycle period. The range of the test variables were:

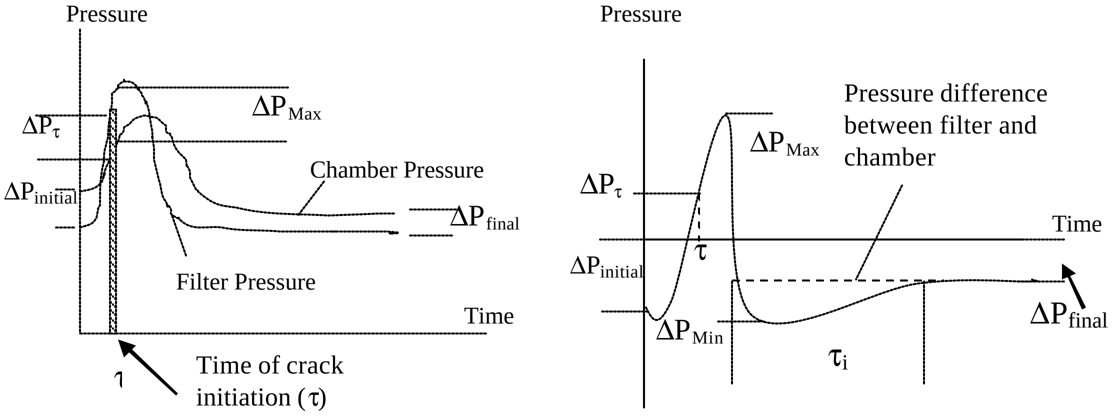
(a) regeneration pressures - 80, 120, and 145 psig
(b) face velocities - 3 and 7 cm/s
(c) cycle period - 10, 45, and 90 min.

The tests were performed on two types of filter, i.e. high permeability and low permeability filters. The high permeability filter was used to determine the base condition as well as for all the independent variables listed. The low permeability filter was also employed for the base condition and then employed for some test conditions which showed regeneration problems for the high permeability filter.

The dependent variables in this study were the cycle-to-cycle surface regeneration efficiency and type of surface regeneration for each test. Surface regeneration efficiencies are discussed relative to the overall problem of minimizing the pressure drop across the filter. Also considered was the type of surface regeneration as the number of cycles increased in each test. The residual ash layer growth was also determined by noting the change in the initial pressure drop across the filter before each surface regeneration event. For several test conditions, the concentration and motion of particles, less than 100µm, were determined using the high resolution, high speed image acquisition system employed in the RTTF.

Data Analysis

The dependent variables will be analyzed separately in this section. However, a common thread links all the analysis together through the pressure diagrams shown in Figure 1. Figure 1(a) shows the typical pressure response in the filter and the chamber during a surface regeneration event. Figure (1b) illustrates the difference between the filter pressure, P_F, and the chamber pressure, P_C. This pressure difference is initially negative, jumps to a positive magnitude during regeneration and then decreases to a smaller negative number. These important pressure differences are $\Delta P_{initial}$, ΔP_{max}, ΔP_{min}, and ΔP_{final}, as shown in Figure 1.



(a) (b)

Figure 1. Schematic of the pressure difference between the filter and the chamber during regeneration

Pressure Difference during Surface Regeneration

The significant pressure difference in this study is the difference between the filter pressure and the chamber pressure. The pressure difference, which dictates if the ash layer will be removed, is ΔP_{max}. Because the failure strength is small for the ash layer, surface regeneration occurred whenever ΔP_{max} exceeded zero. During the filtration period, the filter pressure was kept constant by the laboratory exhaust system. Concurrently, the chamber pressure increased as the ash layer thickness grew in order to maintain the desired face velocity. At the end of the filtration period, the pressure drop across the ash-filter system was a large negative value $\Delta P_{initial}$. In this study, this value was a function of the length of the filtration period and the face velocity. The high-pressure regeneration pulse jet then created a relatively large pressure within the filter. As the surface regeneration process proceeds, the chamber pressure rises due to two inflows and no outflow. The resulting ΔP_{max} is then a function of the regeneration pressure and the initial pressure drop. The pressure difference reaches a stable final value (ΔP_{final}), and this is a function of the resistance offered to flow by the filter and the residual ash, after regeneration. A cleaning factor 'F', which is the ratio of final pressure drop (ΔP_{final}) to pressure drop across a new filter (ΔP_{new}) may be used to compare how clean the filter is after the regeneration.

Number of Test Cycles

As previously stated, the number of cycles completed for each test condition was determined by (1) when the surface regeneration displayed a repeatable process and (2) when the surface regeneration process failed to remove ash from the filter surface. For condition (1), no residual ash remains on the filter surface if repeatability is to occur. For condition (2), the pressure drop across the ash-filter system becomes so great that ΔP_{max} does not exceed the failure stress in the ash layer.

Type of Surface Regeneration

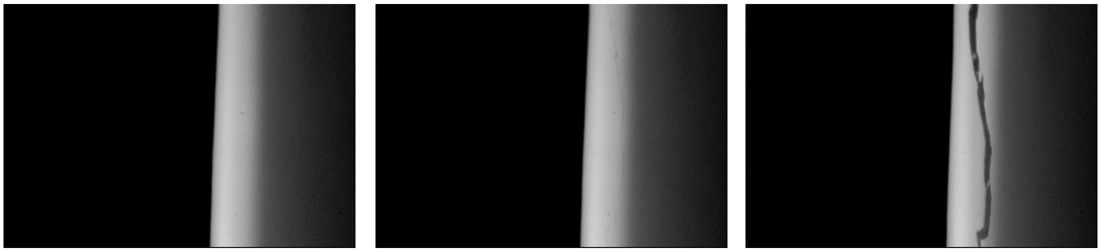
For this experimental investigation, a thick ash layer is described as one in which vertical cracks appear in the ash layer at the beginning of regeneration and chunks of ash fall away from the filter surface during regeneration. This process is shown in Figure 2. Usually, a residual ash layer or patches of ash will remain on the surface. In this research, ash thickness of greater than 1.5mm is considered as thick ash. If the ash appeared to explode from the surface during regeneration, as shown in Figure 3, it is characterized as thin ash. Typically, a thin ash layer has a thickness of no greater than 1mm. For ash layers with a thickness approximately in the range of 1 to 1.5 mm, a process occurred where the ash layer began to disintegrate like a thick ash layer, but as the chunks began to fall away from the surface, the chunks disintegrated into small chunks and particles.

Distributions and Motion of Particles During Regeneration

The concentration and motion of particles near the filter surface plays an important role in re-establishing the ash layer. Immediately after the regeneration pulse, a relatively large pressure drop occurs between the chamber and the filter. This condition appears in Figure 1 and is denoted by ΔP_{min} and exists for a time period τ_i. This larger pressure difference will accelerate particles near the surface towards the surface leading to re-entrainment in the ash layer. The small particles will have a higher probability to be re-entrained during this process. Therefore the distributions of particles less than 100µm were analyzed for different test conditions. The observation of the particle motions during re-entrainment is shown in Figures 4 and 5.

Surface Quality

Surface quality deterioration, marked by residual ash growth and patchy cleaning, increases the pressure drop across the filter. Visible observation and a high resolution imaging system were used in examining and recording the quality of the filter surface immediately after the regeneration process.



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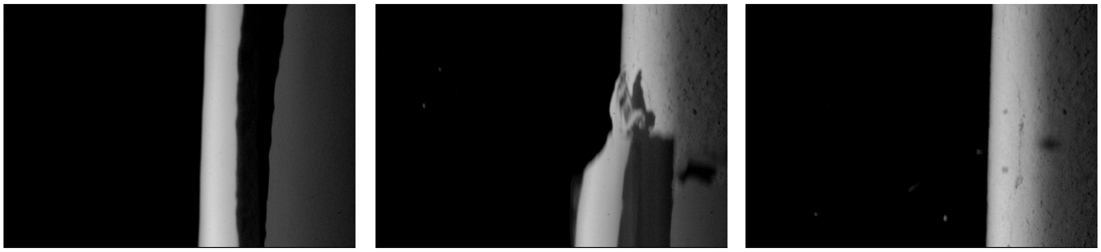

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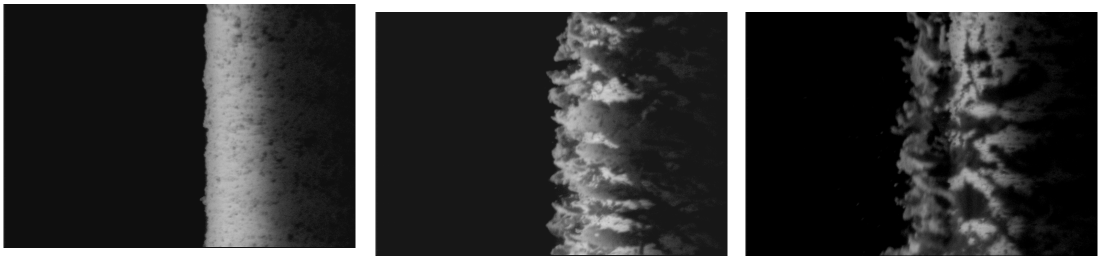
Figure 2. Thick ash regeneration



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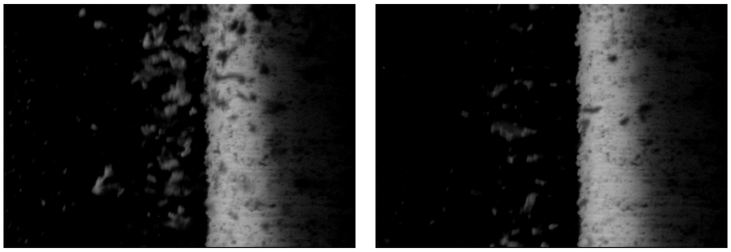

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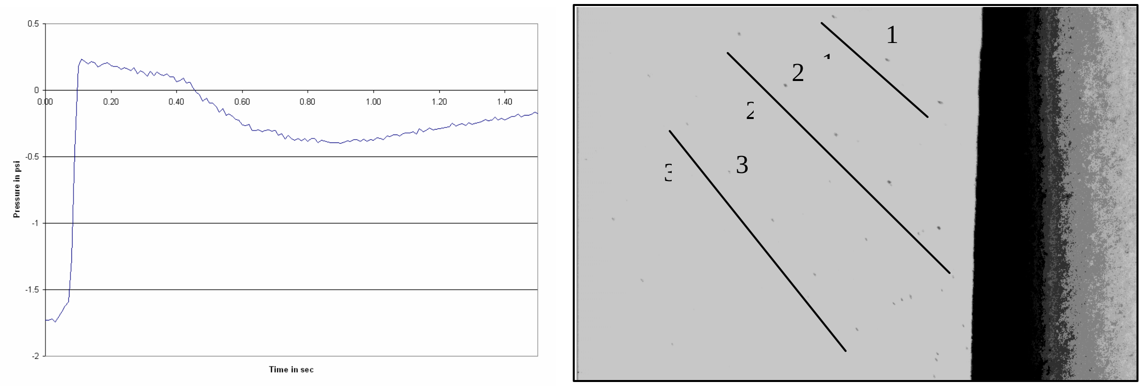
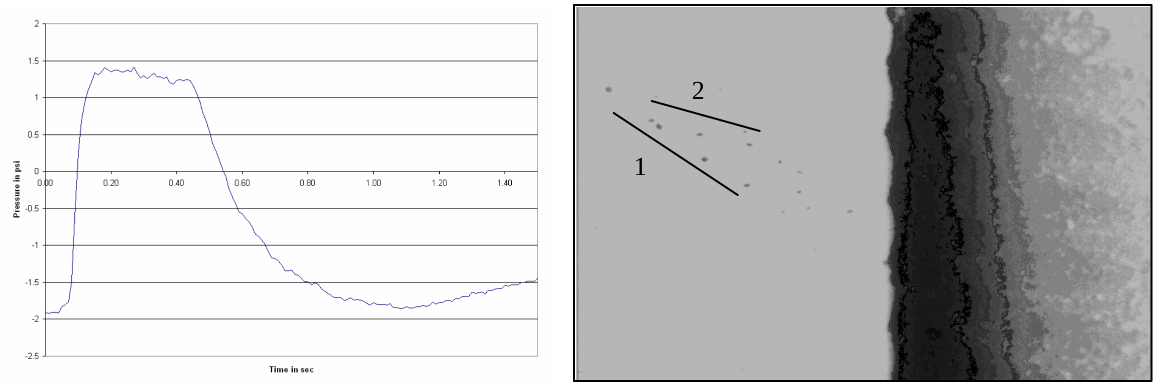
Figure 3. Thin ash regeneration



Track	Particle Size (μ)	Minimum Pressure (Δp-min)	Start Pressure (psi)	End Pressure (psi)	Horizontal Velocity Component (mm/sec)	Vertical Velocity Component (mm/sec)	Velocity (mm/sec)	Orientation (θ) in degrees
1	490	-0.40	-0.19	-0.30	202.65	241.50	315.26	49.99
2	560	-0.40	-0.19	-0.30	193.2	278.25	339.09	55.22
3	420	-0.40	-0.19	-0.30	158.55	289.80	330.46	61.29

Figure 4. Image of particle “re-entrainment” pressure drop curve and image sequence from 0.55 to 0.65 sec, for high-permeability filter - base conditions, 1st test



Track	Particle Size (μ)	Minimum Pressure (Δp-min)	Start Pressure (psi)	End Pressure (psi)	Horizontal Velocity Component (mm/sec)	Vertical Velocity Component (mm/sec)	Velocity (mm/sec)	Orientation (θ) in degrees
1	560	-1.86	-1.52	-1.72	174.30	180.60	251.31	45.71
2	490	-1.86	-1.52	-1.72	183.40	98.00	211.30	27.11

Figure 5. Image of particle “re-entrainment”, pressure drop curve and image sequence from 0.83 to 0.92 sec, for low-permeability filter - base conditions, 4th test

Results and Discussions

The RTTF test results can be used to determine optimal conditions for efficient surface regeneration and are very helpful in designing the tests to be performed at high temperature. A detailed analysis of the room temperature test results is available in reference 4. In this paper, only condensed comparative tables are shown to explain the effect of surface regeneration characteristics. The shaded boxes in these tables correspond to undesirable regeneration characteristics. It should be noted that the optimal parameters suggested are based on the results from the RTTF, and may be system specific.

Effect of regeneration pressure

The regeneration pulse pressure imparts stresses on the ash layer and dislodges it. Cleaning efficiency is expected to increase with increasing regeneration pulse pressure. The regeneration pressures in the study were (a) 80 psig, (b) 95 psig, (c) 120 psig and (d) 145 psig. The 95 psig condition, as mentioned earlier was taken as the base condition. A detailed description of the results is presented in Table 1.

The base build-up conditions (5 cm/s face velocity & 20 min cycle period) resulted in thin ash deposition. The face velocity and the cycle period chosen always resulted in thin ash layers. Failure of filter to regenerate is the easiest way to distinguish the performances, but in all the four pressure conditions the filters continued to regenerate continuously. This can be partially attributed to the build-up conditions. All four conditions displayed thin ash build-up and regeneration. The particle count during regeneration was high, due to thin ash regeneration in all four conditions.

Among the four pressure values, the 80 psig condition displayed more negative characteristics. This is especially highlighted by repeated partial regeneration, relatively high and increasing cleaning factors, and relatively high deterioration of the filter surface quality. With stronger build-up conditions it could be difficult for the filter to regenerate. The 95 psig condition displayed similar regeneration characteristics as 80 psig, but had relatively lower surface deterioration. The cleaning factor value was low and constant. The 120 psig and the 145 psig pressure conditions displayed the most desirable surface regeneration characteristics among all four conditions. Surface deterioration was very low and the filter had thin and sparse residual ash on its surface in these cases. Since both the 120 psig and 145 psig regeneration pressure conditions perform similarly, 120 psig can be preferred over 145 psig as the optimal regeneration pressure. The same amount of cleaning is achieved with smaller cleaning system and lower energy expenditure.

Effect of face velocity

Face velocity affects the density, thickness and strength of the ash cake. The face velocities employed in the study were (a) 3 cm/s, (b) 5 cm/s and (c) 7cm/s. A face velocity of 5 cm/s was taken as the base condition. A comparative table (Table 2) is shown here to discuss the results.

The 7 cm/s condition caused the filter to perform poorly, for the selected base conditions. The filter failed to regenerate on the 7th cycle, while the 3 cm/s and 5 cm/s conditions continued to regenerate. There substantial increase of chamber pressure is highest in the 7 cm/s condition, due to the high rate of ash transported to the ash layer.

The pressure difference during the interim time period was large and could have caused a significant amount of particle re-entrainment. The cleaning factor was large and kept increasing with each cycle for 7 cm/s condition. The crack initiation time was the longest on 7 cm/s and the filter had thick residual ash cakes. It can be concluded that the 7 cm/s face velocity is not desirable for efficient filter regeneration, for the given base conditions.

Among the 3 cm/s and 5 cm/s face velocity conditions, there was not much difference in their performance. Surface deterioration was about the same for both conditions (after 15 cycles). Both conditions built thin ash and displayed thin ash regeneration. A major drawback in both conditions was the significantly higher particle count, due to thin ash regeneration. A face velocity of 5 cm/s is preferred over 3 cm/s as the optimal face velocity. Although they exhibit similar performances, a higher face velocity will help saving time and energy.

Effect of cycle period

An increase in cyclic ash deposition period resulted in more ash being collected on the surface of the filter between regeneration events. The cyclic deposition periods in the study were (a) 10 min., (b) 20 min., (c) 45 min. and (d) 90 min. The 20 min. period was used as the base condition. The results are shown in Table 3.

The filter failed to regenerate on the 5th cycle for the 45 min. cyclic deposition period and on the 1st cycle for the 90 min. case. As expected, a longer deposition period formed a thicker ash layer, which caused less efficiency in ash regeneration. The two longer period conditions resulted in increased chamber pressures and large negative ΔP_{min} values that further deteriorate the cleaning action of the pulse jet. Their cleaning factors were larger and increasing with each regeneration cycle. They built strong residual ash cakes on the filter surface and eventually stopped the regeneration. The crack initiation time was long in the 45 min. condition and could not be observed in the 90 min. condition (which failed to regenerate even in the 1st cycle). The 45 min. and 90 min. cyclic deposition periods are not desirable for efficient filter regeneration, with other base parameters selected.

The 10 min. and 20 min. cycle periods exhibited similar performances. Surface quality deterioration was about the same for both conditions (after 15 cycles). Both conditions built thin ash layer and displayed thin ash regeneration. A major drawback in both these conditions was the significantly higher particle count, due to thin ash regeneration. The 20 min. cycle period imparts similar cleaning, less frequently, as compared to the 10 min. cycle period. Therefore a 20 min. cycle period can be chosen as the optimal cleaning cycle period.

Effect of filter type

The permeability of the filters was measured as a function of pressure drop across clean filter. Clean air at different face velocities was passed through the filters and the pressure drop measured. The filters were then classified as “low permeability” filter or “high permeability” filter. The test conditions chosen for the comparative study corresponded to base conditions, as well as the conditions for which the surface regeneration may be difficult for high permeability filter. The conditions were (a) lower regeneration pressure (80 psig), (b) higher face velocity (7cm/s) and (c) longer cycle periods (45 min. and 90 min.).

The “high permeability” filter performed better than the “low permeability” filter in all the limiting cases. The “high permeability” filter lasted longer than the “low permeability” filter, in conditions when both filters failed to regenerate - 7 cm/s face velocity and 90 min. cycle period conditions. The “low permeability” filter failed to regenerate on the 5th cycle in the 45 min. cycle period condition, while the “high permeability” filter lasted for 16 cycles, and continued to regenerate. The values of the cleaning factors and ΔP_{min} were consistently better in “high permeability” filter, compared to “low permeability” filter. The surface quality deterioration was lower in “high permeability” filter and performed better than the “low permeability” filter. “High permeability” filter should be preferred to “low permeability” filter, based on the test results

Conclusion

A room temperature testing facility was built to study ash particle distribution characteristics of candle filter surface regeneration. The processing variables investigated in this study were (1) magnitude of the regeneration pressure, (2) facial velocity on the filter surface, (3) cycle frequency (or filtration period), and (4) filter wall permeability characteristics. Tests were conducted at a selected set of conditions on two types of filters (high permeability and low permeability filters). The effect of each processing parameter as well as the optimal conditions for the efficient removal of the ash layer during surface regeneration were studied.

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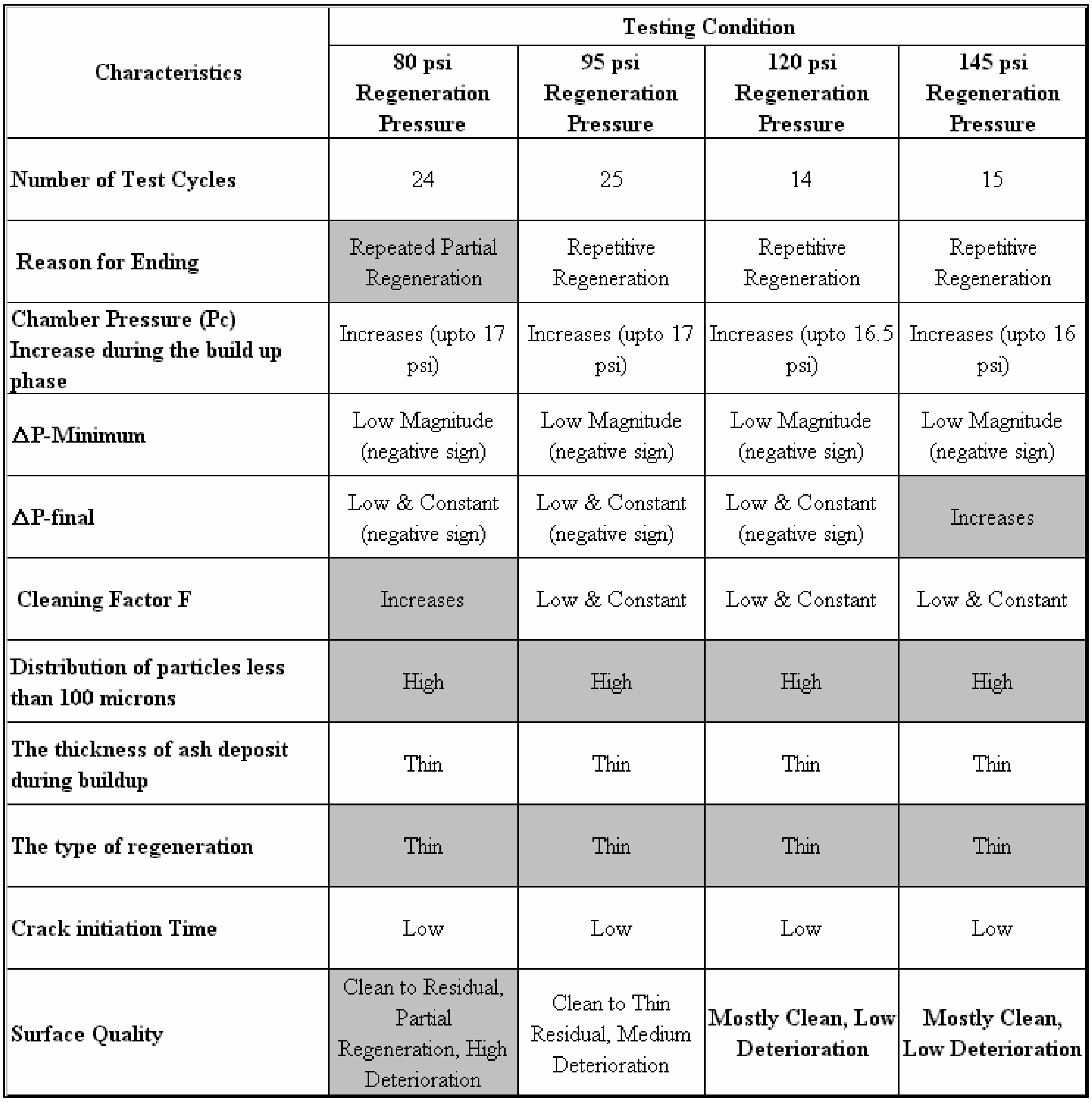
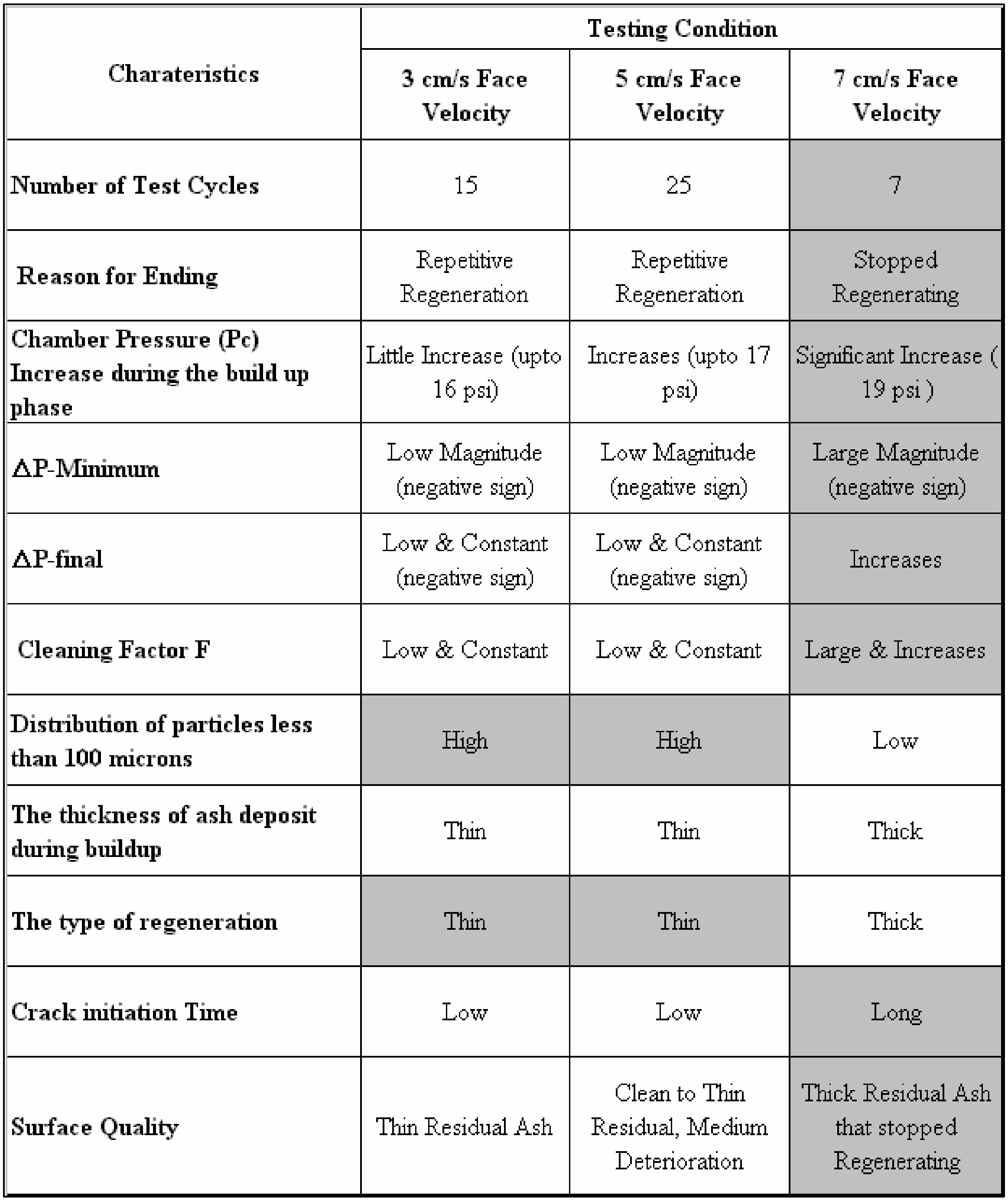


Characteristics	Testing Condition			
	80 psi Regeneration Pressure	95 psi Regeneration Pressure	120 psi Regeneration Pressure	145 psi Regeneration Pressure
Number of Test Cycles	24	25	14	15
Reason for Ending	Repeated Partial Regeneration	Repetitive Regeneration	Repetitive Regeneration	Repetitive Regeneration
Chamber Pressure (Pc) Increase during the build up phase	Increases (upto 17 psi)	Increases (upto 17 psi)	Increases (upto 16.5 psi)	Increases (upto 16 psi)
ΔP-Minimum	Low Magnitude (negative sign)	Low Magnitude (negative sign)	Low Magnitude (negative sign)	Low Magnitude (negative sign)
ΔP-final	Low & Constant (negative sign)	Low & Constant (negative sign)	Low & Constant (negative sign)	Increases
Cleaning Factor F	Increases	Low & Constant	Low & Constant	Low & Constant
Distribution of particles less than 100 microns	High	High	High	High
The thickness of ash deposit during buildup	Thin	Thin	Thin	Thin
The type of regeneration	Thin	Thin	Thin	Thin
Crack initiation Time	Low	Low	Low	Low
Surface Quality	Clean to Residual, Partial Regeneration, High Deterioration	Clean to Thin Residual, Medium Deterioration	**Mostly Clean, Low Deterioration**	**Mostly Clean, Low Deterioration**

Table 1. Comparative table – effect of regeneration pressure
Face velocity – 5 cm/s, cycle period – 20 min



Charateristics	Testing Condition		
	3 cm/s Face Velocity	5 cm/s Face Velocity	7 cm/s Face Velocity
Number of Test Cycles	15	25	7
Reason for Ending	Repetitive Regeneration	Repetitive Regeneration	Stopped Regenerating
Chamber Pressure (Pc) Increase during the build up phase	Little Increase (upto 16 psi)	Increases (upto 17 psi)	Significant Increase (19 psi)
ΔP-Minimum	Low Magnitude (negative sign)	Low Magnitude (negative sign)	Large Magnitude (negative sign)
ΔP-final	Low & Constant (negative sign)	Low & Constant (negative sign)	Increases
Cleaning Factor F	Low & Constant	Low & Constant	Large & Increases
Distribution of particles less than 100 microns	High	High	Low
The thickness of ash deposit during buildup	Thin	Thin	Thick
The type of regeneration	Thin	Thin	Thick
Crack initiation Time	Low	Low	Long
Surface Quality	Thin Residual Ash	Clean to Thin Residual, Medium Deterioration	Thick Residual Ash that stopped Regenerating

Table 2. Comparative table – effect of face velocity
Regeneration pressure – 95 psig, cycle period – 20 min

Characteristics	Testing Condition			
	10 min Cycle Period	20 min Cycle Period	45 min Cycle Period	90 min Cycle Period
Number of Test Cycles	15	25	5	1
Reason for Ending	Repeated Partial Regeneration	Repetitive Regeneration	Stopped Regenerating	Stopped Regenerating
Chamber Pressure (Pc) Increase during the build up phase	Increases (upto 17 psi)	Increases (upto 17 psi)	Significant Increase (19 psi)	Significant Increase (21.5 psi)
ΔP-Minimum	Low Magnitude (negative sign)	Low Magnitude (negative sign)	Large Magnitude (negative sign)	Large Magnitude (negative sign)
ΔP-final	Low & Constant (negative sign)	Low & Constant (negative sign)	Increases	Increases
Cleaning Factor F	Low & Constant	Low & Constant	Large & Increases	Large & Increases
Distribution of particles less than 100 microns	High	High	Low	Not Observable
The thickness of ash deposit during buildup	Thin	Thin	Thick	Thick
The type of regeneration	Thin	Thin	Thick	Thick
Crack initiation Time	Low	Low	Not Observable	Not Observable
Surface Quality	Thin Patchy Residuals	Clean to Thin Residual, Medium Deterioration	Thick Residual that did not regenerate	Thick Residual that did not regenerate

Table 3. Comparative table – effect of cycle period
Regeneration pressure – 95 psig s, face velocity – 5 cm/s

Characteristics	Testing Conditions									
	Base		80 psi Regeneration Pressure		7 cm/s Face Velocity		45 min Cycle Period		90 min Cycle Period	
Filter Permeability	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Number of Test Cycles	25	22	24	24	7	15	5	16	1	3
Reason for Ending	Repetitive Regeneration	Repetitive Regeneration	Repeated Partial Regeneration	Repetitive Regeneration	Stopped Regenerating	Stopped Regenerating	Stopped Regenerating	Repetitive Regeneration	Stopped Regenerating	Stopped Regenerating
Chamber Pressure (Pc) Increase during the build up phase	Increases (upto 17 psi)	Increases (upto 17 psi)	Increases (upto 17 psi)	Increases (upto 17 psi)	Significant Increase (19 psi)	Significant Increase (20 psi)	Significant Increase (19 psi)	Significant Increase (19 psi)	Significant Increase (21.5 psi)	Significant Increase (20 psi)
ΔP-Minimum	Large Magnitude (negative sign)	Low Magnitude (negative sign)	Large Magnitude (negative sign)	Low Magnitude (negative sign)	Large Magnitude (negative sign)	Low Magnitude (negative sign)	Large Magnitude (negative sign)	Low Magnitude (negative sign)	Large Magnitude (negative sign)	Low Magnitude (negative sign)
ΔP-final	Large Magnitude (negative sign)	Low Magnitude (negative sign)	Large Magnitude (negative sign)	Low Magnitude (negative sign)	Large Magnitude (negative sign)	Low Magnitude (negative sign)	Large Magnitude (negative sign)	Low Magnitude (negative sign)	Large Magnitude (negative sign)	Low Magnitude (negative sign)
Cleaning Factor F	Higher	Lower	Higher	Lower	Higher	Lower	Higher	Lower	Higher	Lower
Distribution of particles less than 100 microns	High	Low	High	High	High	Low	Low	Low	Not Observable	Low
The thickness of ash deposit during buildup	Thin	Thick	Thin	Thick	Thick	Thick	Thick	Thick	Thick	Thick
The type of regeneration	Thin	Thick	Thin	Thin	Thick	Thick	Thick	Thick	Not Observable	Thick
Crack initiation Time	Low	Low	Low	Low	Long	Long	Thick & Not Observable	Long	Not Observable	Long
Surface Quality	Relativley more Deterioration	Lesser Deterioration	Relativley more Deterioration	Lesser Deterioration	Thick Residual Ash that stopped Regenerating	Thick Residual Ash that stopped Regenerating	Thick Residual that did not regenerate	Residual Dust Layer	Thick Residual that did not regenerate	Thick Residual that did not regenerate
Constant Conditions	Base Conditions		Face velocity, Cycle period		Regeneration pressure, Cycle period		Regeneration pressure, Face Velocity		Regeneration pressure, Face Velocity	

Table 4. Comparative table – effect of filter type