Ash Behavior in Wall-flow Filters

In wall-flow filters, ash accumulates with increasing runtime, which upscales the back pressure of the exhaust system in the long term. Depending on the operating conditions, it accumulates in several ways with different effects. As part of the FVV project "Ash behavior in wall-flow filters" (FVV No. 1292), experiments and simulations were carried out at TU Braunschweig and the University of Wuppertal to investigate the parameters influencing the type of ash deposition.

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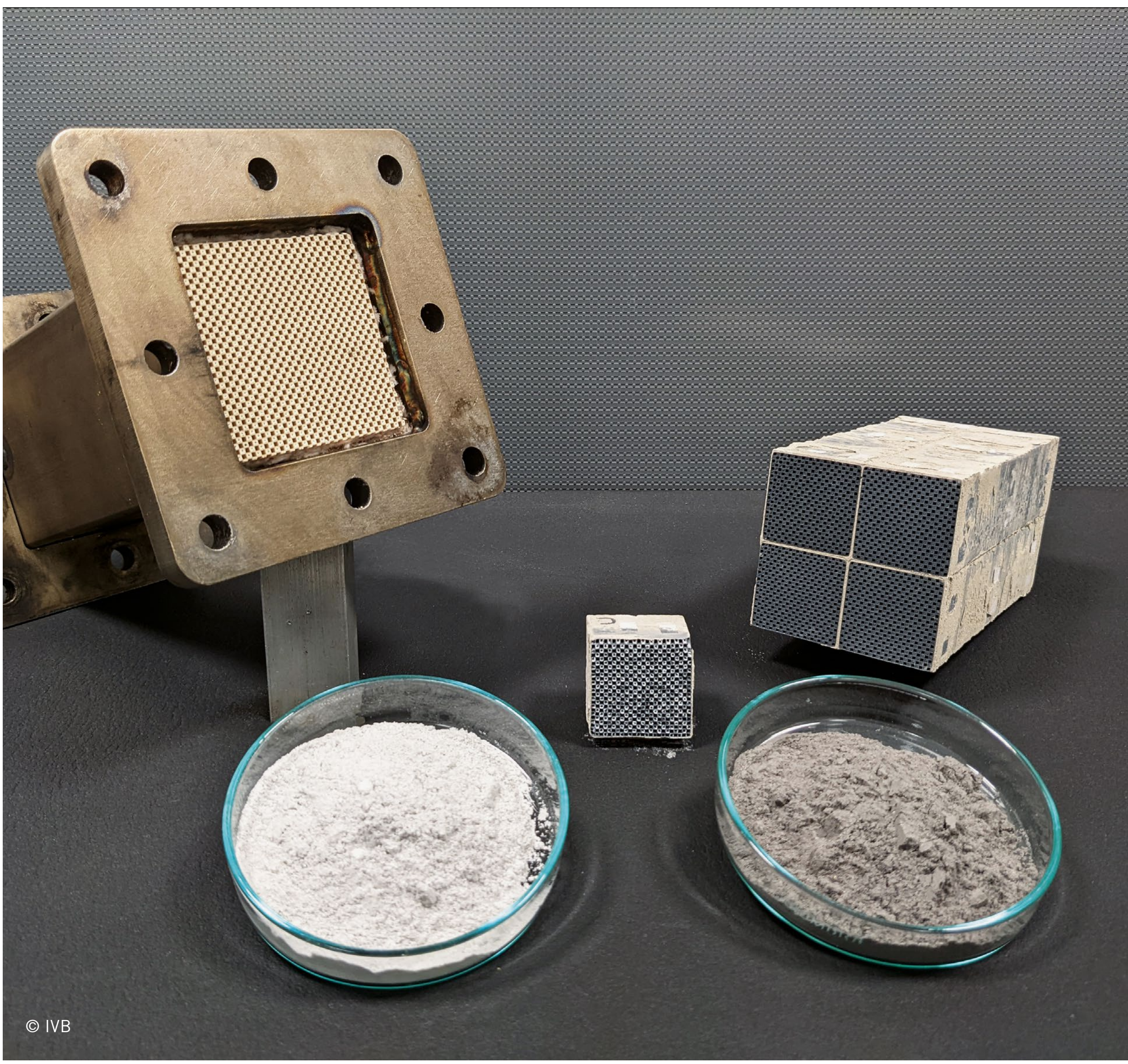

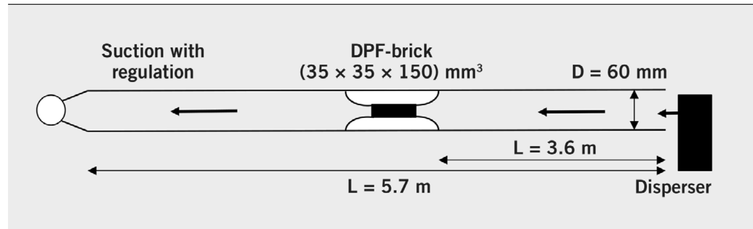

FIGURE 1 Schematic construction of wind channel at the IPT (© IPT)

1 MOTIVATION

While soot deposited in Diesel Particulate Filters (DPF) can be removed from the filter again by thermal or continuous regeneration, ash particles remain in the filter as an inorganic residue and increase the backpressure [1, 2]. There are two theoretical limiting cases for ash deposition: Ash can be deposited along the channel walls or form a plug at the end of the channel [3]. The parameters influencing the deposition patterns interact in a complex structure that drives up the costs of experiments for prediction. The investigations carried out at the Institute of Internal Combustion Engines (IVB) of TU Braunschweig and at the Chair of Fluid Mechanics (LSM) and the Institute of Particle Technology (IPT) of the University of Wuppertal [4] contribute to a fundamental understanding of the ash processes in the filter. These findings, which could be transferred to simulations, reduce the development effort of DPFs.

2 TEST BED DESIGN

The experimental investigations were carried out at the IPT and at the IVB. The IPT used a modified wind channel for loading and unloading filter samples with an ash substitute, **FIGURE 1**. The tests at the IVB were carried out under real operating conditions and were performed using a rapid ashing system, in which the soot and ash input into the engine exhaust gas can be increased by adding exhaust gas from a diesel burner with oil injection. To increase the density of information within each loading run, the

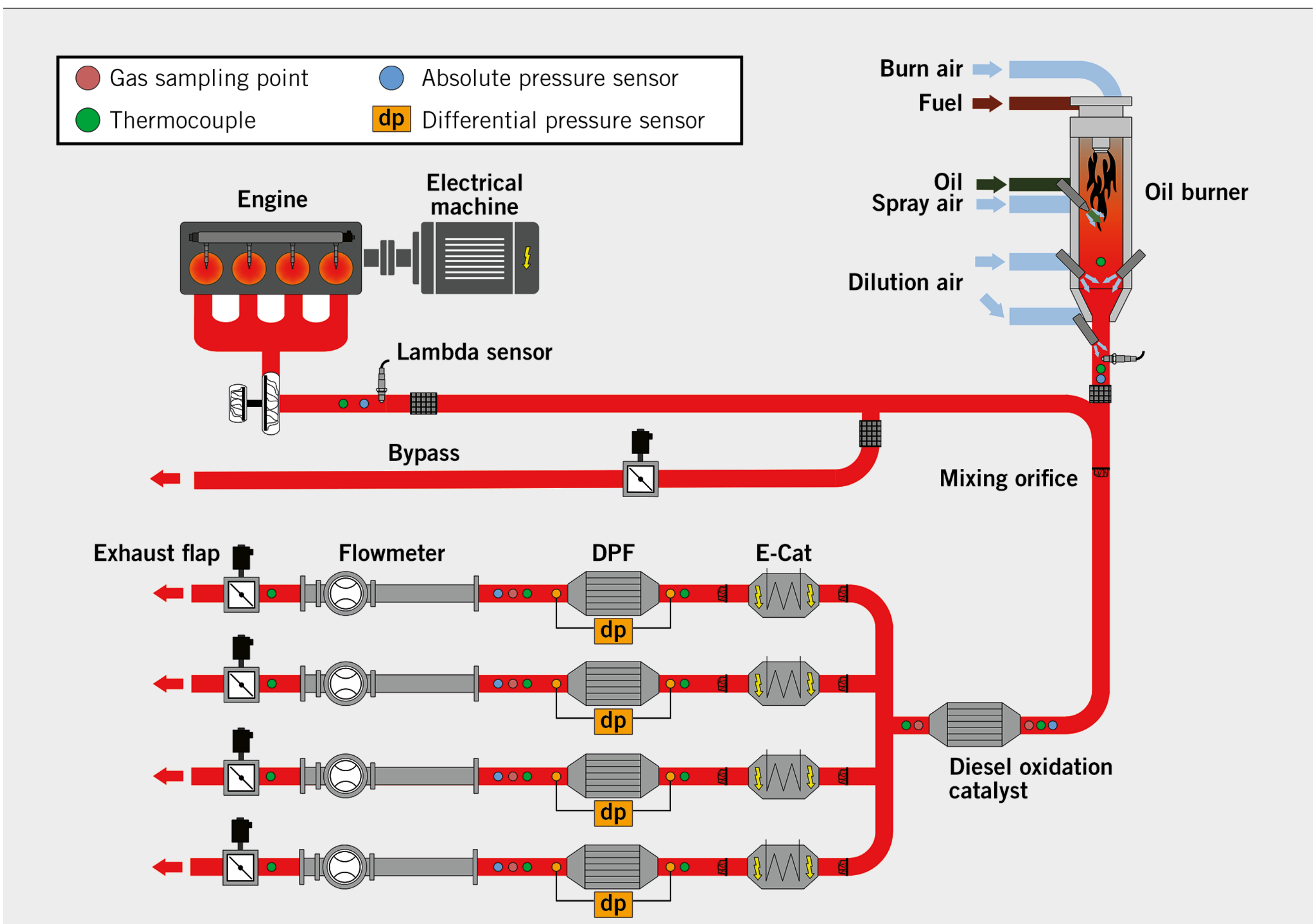

FIGURE 2 Schematic overview of the rapid and multi ashing system at the IVB (© IVB)

Filter no.	m_{dust} [g]	$v_{channel}$ [m/s]	$c_{channel}$ [g/m³]	l_{plug} [mm]	Δ porosity [-]
6	3.6	1	0.5	17.9	0.59
8	7.4	1	0.5	58.6	0.79
7	10.0	1	0.5	89.4	0.83
12	3.4	0.4	0.5	-	-
13	3.7	0.8	0.5	34.3	0.84
14	3.3	1.2	0.5	8.6	0.44
15	2.2	1	0.3	10.7	0.70
16	2.7	1	0.4	13.9	0.72
17	3.1	1	0.6	16.1	0.72
18	3.0	1	1.3	12.6	0.66

TABLE 1 Results of wind channel tests with variation of the parameters m_{dust}, $v_{channel}$ and $c_{channel}$ (© IPT)

rapid ashing system was equipped with multiple exhaust lines. The so-called multi ashing system allows simultaneous loading of several filters under defined conditions, **FIGURE 2**.

3 STORAGE BEHAVIOR

For the investigation of the storage behavior of ashes in filter bricks, a suitable ash substitute was found by comparing numerous physical and chemical parameters with the calcium carbonate Ulmer Weiss XMF. By dispersion in the previously described wind tunnel, the filter bricks could be loaded under variation of the input parameters absolute load mass m_{dust}, inflow velocity $v_{channel}$ and raw gas concentration $c_{channel}$. Afterwards, all filter bricks were equilibrated at 20 °C for 24 h, weighed and fed to the computer tomograph for the measurement of the plug height l_{plug}. For further evaluation the values for l_{plug} were compared with the gravimetric effects of the deposits.

In all cases, however, the gravimetric determination showed a smaller mass increase than expected. The percentage deviation from the expected density was defined as additional porosity and represents a key parameter in the assessment of the storage. It can be derived from **TABLE 1** that the variation of the test parameters of the storable mass and the average velocity in the wind tunnel has an influence on the storage behavior of the test material in the filter brick. With a higher load, the additional porosity increases. With increasing inflow velocity, the additional porosity is reduced. A variation in the concentration in the raw gas appears to have no effect on the formation of the inlays in the filter brick.

4 REGENERATION BEHAVIOR

For real loading of the DPF substrates, regeneration in particular was varied with otherwise largely identical conditions. The operation data above the respective sample was set by a combination of different engine and burner operating points as well as the flap position of the multi ashing system. Deposition patterns were evaluated by breaking the substrates segment by segment with subsequent image analysis.

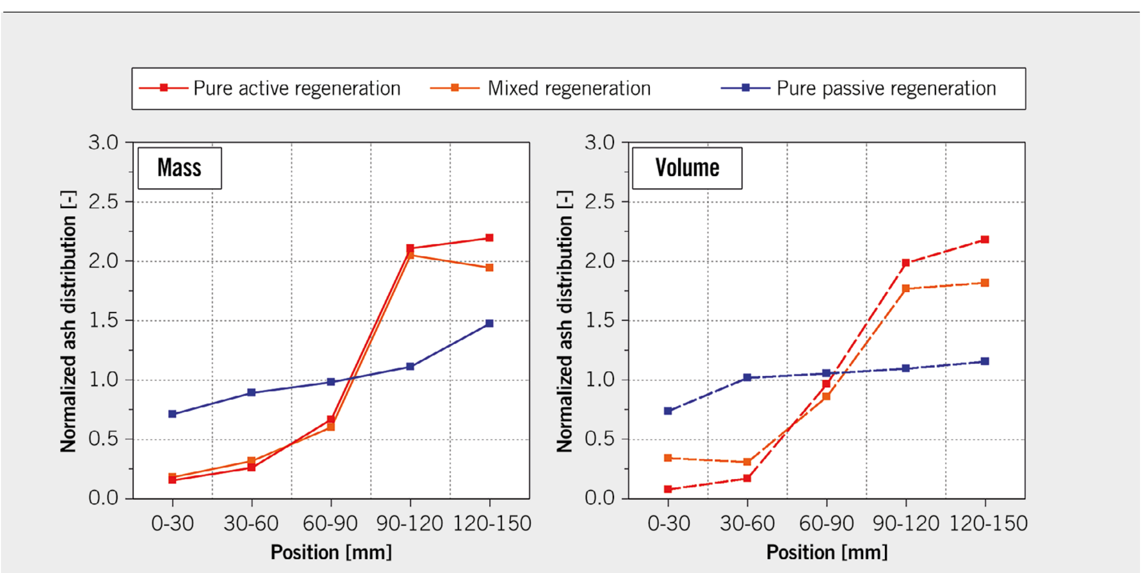

FIGURE 3 Normalized ash distribution of active, mixed and passive regeneration with respect to mass (left) and volume (right) (© IVB)

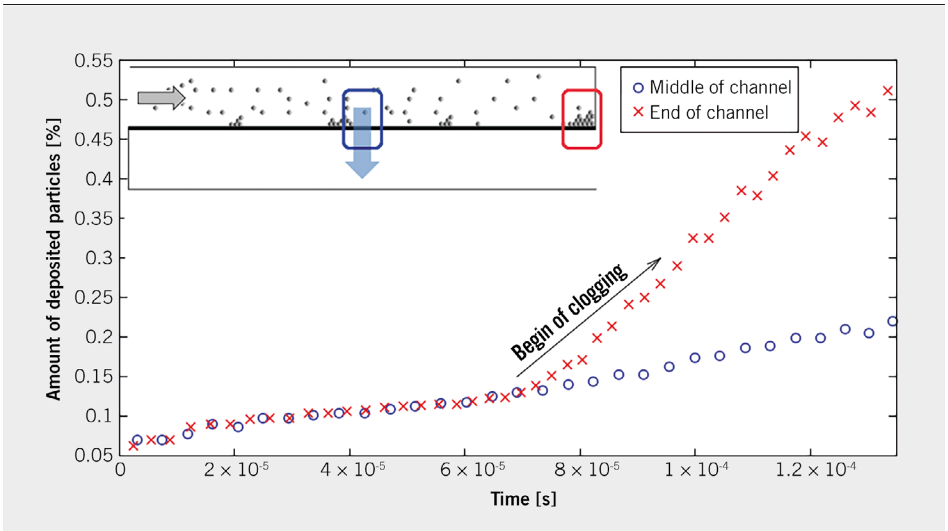

FIGURE 4 Particles separated as a percentage of the total number in the simulated DPF section, and illustration of the affected sections in the inlet channel (© LSM)

The influence of the regeneration temperature T_{Reg} was investigated on the one hand, with regard to the discontinuous soot burnup by the reaction with O_2 (T_{Reg} = 575/625 °C) and, on the other hand, by the reaction with NO_2 (T_{Reg} = 350/450 °C). In both cases, the ash deposited in the filters mainly as ash plugs. At approximately the same ash loading, these plugs become smaller with increasing regeneration temperature and the ash packing density in the plug increases. Particularly at very low regeneration temperatures, a distinct wall layer is also formed. This is mainly characterized by a coarse, uneven structure. In general, there are indications that the ash density in the wall layer decreases with increasing regeneration temperature. The observations indicate that at higher temperatures more ash agglomerates are released from the wall layer as loosening and transported to the channel end with the effect of compaction.

To investigate the influence of the type of regeneration, a comparison was made between continuous and discontinuous regeneration and a mixture of the two. **FIGURE 3** shows the normalized ash distribution for all three filters. Continuous regeneration leads to the formation of a wall layer that becomes thicker towards the back and increases in packing density. In some cases, a detachment of the ash layer from the filter wall can be observed in the front area of the filter. Discontinuous regeneration shows the plug formation already mentioned. In the case of mixed regeneration, the ash is also deposited as a plug. However, it is noticeable that a thin wall layer is also formed and that the ash packing density in the plug is up to 50 % higher in the mixed regeneration than in the purely active continuous one. It is conceivable that more unstable structures with a larger resuspension surface are present within the wall layer, which form as a result of the partially continuous soot burnup. Overall, the formation of an ash plug always occurs only through discontinuous regeneration.

The consideration of the flow velocity was carried out for the case of continuous regeneration as well as for discontinuous regeneration. Even a quadrupling of the flow velocity in the case of continuous regeneration does not lead to plug formation in the channel. Instead, a dense wall layer is formed, which increasingly adapts to the channel shape as the flow velocity increases. With discontinuous regeneration, a doubling of the flow velocity leads to 30 % denser ash plugs. However, an additional wall layer is formed along the channel. Due to the electric heating elements used in the system, the regeneration temperature is reached more slowly, resulting in slower soot burnup, which presumably makes wall ash detachment more difficult.

5 NUMERICAL SIMULATION RESULTS

Experimental investigations have been accompanied by numerical simulations of soot burn-off and ash migration. All calculations have been performed in the open source software toolkit OpenFoam. It has been expanded by an in-house developed Immersed Boundary Method (IBM) which is used to describe the disperse phase. An IBM is characterized by the fact that the influence of the objects in the fluid on the flow does not have to be modeled for every possible geometry, but follows directly from the integration of generally valid source terms. Furthermore, fluid forces, from which, for example, particle trajectories follow, can be interpolated directly from the computational grid of the fluid to the surface of the object locally resolved. This results in further model independence. The geometry independence was supplemented by general adhesion, collision and agglomeration methods. This has resulted in an overall package that can be used to numerically describe both the adhesion and detachment of arbitrarily shaped particle geometries in a DPF.

First the different deposition behavior in the middle and at the end of a DPF inlet channel has been numerically simulated. The middle region is defined in this way: by particles being able to leave the simulation domain through outlets in the wall or at the end of the domain, which corresponds to a further transport in the disperse phase. The simulation calculations of the channel end section show that the transport is not possible here and the particles are separated at the clogged channel wall. The results of the calculations for both positions in the DPF are shown in **FIGURE 4**. The formation of a plug at the end of the channel can be clearly seen.

Investigations regarding re-entrainment of a deposited particle quantity with and without reactivity have been calculated with material parameters according to experimental data. The results

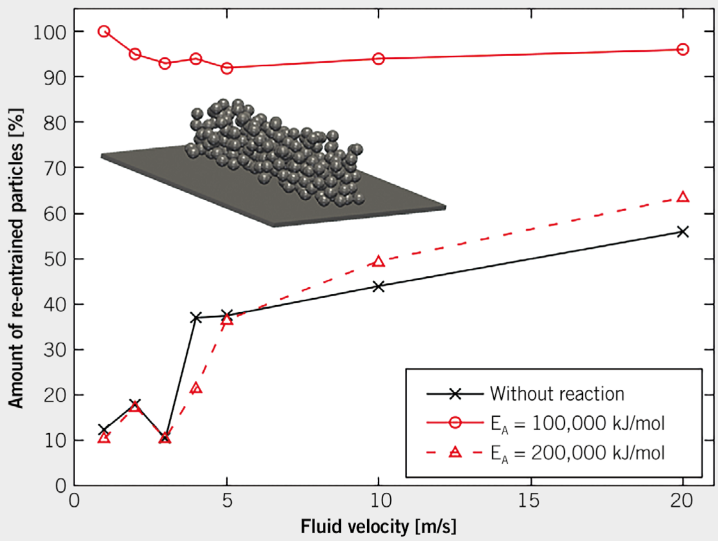

FIGURE 5 Influence of the reactivity E_A on particle re-entrainment and illustration of the substrate with the soot layer consisting of 200 volumetrically resolved particles (© LSM)

in **FIGURE 5** illustrate the difference in detached particle numbers with and without reactivity. In particular, it can be seen that much of the detachment without reactivity begins at a fluid velocity of 5 m/s. This is similar to the empty channel velocity of 20 m/s in the IPT measurements at the level of the particle fill.

6 SUMMARY

The behavior of ash in wall-flow filters was investigated as a function of different operating parameters. At the IPT, an ash substitute was found in the form of Ulmer Weiß XMF, which is readily available and harmless to health as well as exhibiting essential properties of real ash. In addition, a wind channel was modified for loading particle filter bricks. During the wind channel tests, it was possible to determine in particular the influences of flow velocity, loading mass and ash concentration in the raw gas. As part of the investigations at the IVB, a rapid and multi ashing system was developed and set up. By using the system, it was possible to load a large number of sample substrates with engine ash under realistic conditions in very short test times and to analyze them subsequently. In particular, the parameters regeneration temperature, regeneration type and flow velocity were considered and their influence on ash mobility was determined.

In the simulative part of the project, several models were developed at the LSM to describe the interaction of volumetrically resolved particles and their oxidation. The novel model for the description of particle collisions allows the collision forces of arbitrary object geometries to be determined and is inherently energy conserving. The agglomeration process is modeled similarly via conservation laws as the collision resolution, but here momentum and angular momentum are the defining quantities and thus they are inherently conserved. For the calculation of the adhesion forces, a method was developed in this project for the first time, which is purely based on a decomposition of the 3-D geometry (in STL Format) into segments of half-spaces, thus immensely reducing the time required for the calculation. Final simulations have shown that the developed models are capable of representing the transport behavior of matter in a DPF channel with flow.

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