GE Additive

# Continuous Improvement in Gas Flow Design

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# Gas Flow Design

Additive technologies have evolved rapidly from a combination of independent laser, powder, software and gas flow subsystems, into the highly sophisticated machine architectures we see today.

## INTRODUCTION

Users of additive manufacturing machines expect the highest quality when it comes to the mechanical properties of parts, the usability of the machines and associated processes and overall machine design. A main contributor to the quality of the part is the involvement of process-related by-products originating from the melting process.

In order to handle these by-products in additive manufacturing - in the case of laser powder bed fusion (LPBF) - an efficient gas flow over the build plate is required to enable high build rates, clean melting processes and for the effective evacuation of the by-products, such as soot and spatter.

Over the last few years, the understanding of melt pool processes and the importance of gas flow has been evolving. Today, it is possible to specifically optimize the gas flow design in the process chamber to contribute to a clean and efficient build process.

This whitepaper focuses on the evolution of the gas flow during recent continuous improvement efforts on GE Additive Concept Laser M2 machines and how the associated build process was improved due to in-depth research into the underlying physics of the melting process.

## Why is the gas flow over the build plate so important to the laser additive manufacturing process?

In short, spatter and soot problems can be tackled by a well-designed gas flow. To achieve decent build rates, the melt pool, that is created when the laser beam power is absorbed locally by the powder bed, surpasses the boiling temperature of the powder material.

As a result, a vapor jet is formed at the melt pool surface, that ejects vaporized metal and entrained powder from the surrounding and liquid melt pool particles. This vapor condensates into black soot particles and the entrained powder partially agglomerates while being ejected.

Subsequently, the laser beam might potentially hit the soot particles, before hitting the powder bed. And in the absence of a well-designed gas flow, soot particles might even reach the laser window at the top of the process chamber. When that occurs, soot-laser interaction might lead to refraction and absorption of the laser beam, and consequently to a reduction in laser power and beam shape distortion.

Also, virgin powder and spatter particles that land on the to-be-printed powder bed may cause a lack-of-fusion and consequently, pores. Figure 1 depicts several mechanisms of laser-matter interaction and how gas flow can contribute to improving the situation. These phenomena can be influenced by a well-designed gas flow to ensure that ejecta do not impair the printing process, thus ensuring high build rates and high-quality parts. If particles are too large - around several hundredths of a micron - the gas flow cannot transport them efficiently. GE Additive has developed several effective solutions to minimize this type of particle.

However, by improving the gas flow with respect to speed and distribution quality, part density and surface roughness can be significantly improved [1] [2] [3] [4].

## The basic physics of plume and spatter formation during melting

In this section we consider how to improve the additive manufacturing process by further developing the gas flow system accordingly to increase understanding of the physics involved.

Figure 1 also depicts the physics involved in laser-melt pool interaction with a laser beam, with gaussian-shaped power distribution hitting the powder bed.

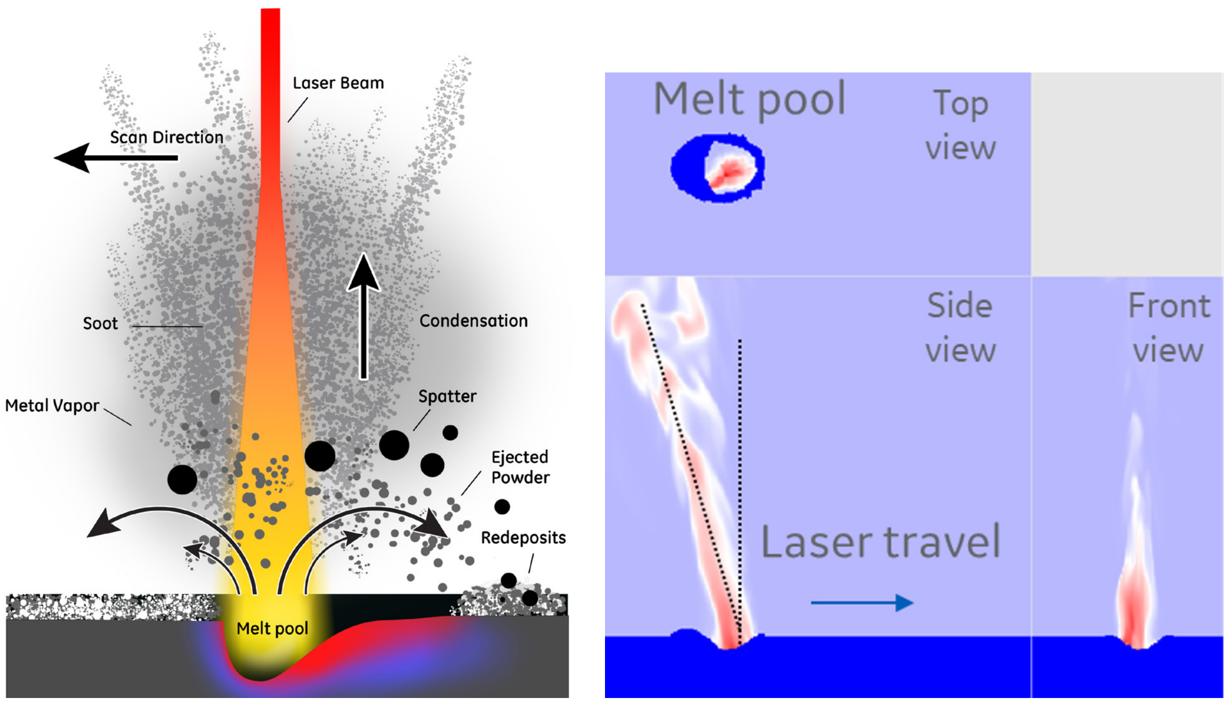



**Figure 1:** Conceptual depiction of interaction of powder, laser, and soot plume (left) and simulation results of showing temperature distribution (right). Image credit: GE Additive

Depending on the powder material properties and size-distribution, the laser power, beam shape and scan speed, the melt pool is formed with a characteristic shape.

Several well-documented effects [5] [6] [7] [8] are apparent while the beam moves over the powder bed, such as Marangoni-convection in the tail of the melt pool, recoil-pressure-induced depression, governing the laser power absorption and molten-metal vortex formation.

On the surface of the depression the temperature locally exceeds the boiling temperature of the metal, which leads to the evaporation of the molten material. The deeper the depression, such as when key-holing appears, the higher the local surface temperature. Depending on the laser-material combination, temperatures of several thousand degrees Kelvin can be observed, which is also associated with very high local pressure (difference, compared to the melt pool surroundings).

The evaporated material is thrusted away from the melt pool surface forming a high-speed jet, which is associated with three different kinds of ejecta being transported away from the melt pool:

1. At high build rates, assuming high melt pool temperatures, a metal vapor jet is formed, which is thrusted into the build chamber at near local sonic speed. Due to the very high momentum of this jet, the gas flow cannot carry the plume away to just above the melt pool. Instead, the jet rises a few tenths of a millimeter into the build chamber where its momentum is decreased. The formerly hot jet is sufficiently cooled down, condensation occurs, forming blackish nanosized particles or so-called soot. The jet is now slower too, and due to lower momentum, it can be easily transported away by a more gradient-free gas flow, since smaller particles follow well in the flow field. Figure 6 depicts the typical soot streamlines in a GE Additive Concept Laser M2 Series 4 machine.

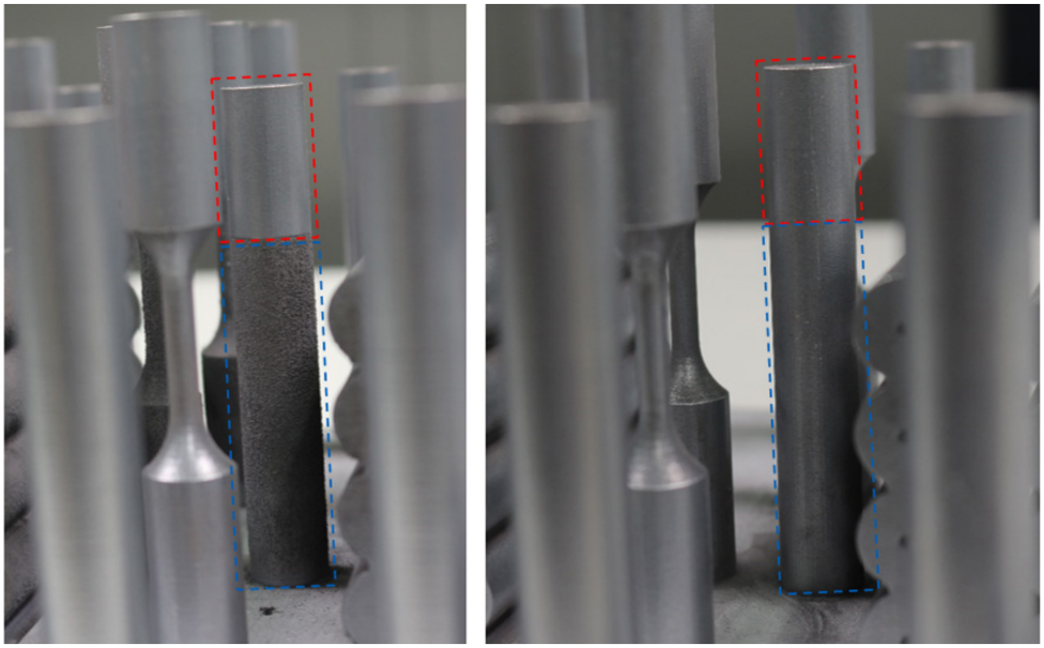
2. Molten droplets which are being transported away from the melt pool and directly interfering with the jet. Depending on the size of these particles, their trajectory is just a few centimeters, before they fall back onto the powder bed. A well-designed gas flow transports these particles as far as possible towards the rim of the build plate. Particles larger than a hundred microns fall back onto the powder bed only a few centimeters away from their origin. These particles are too large and too heavy (compared to the gas flow) to be transported away in an efficient manner.

3. Unmolten powder particles that are sucked in by the entrained co-flow caused by the hot vapor jet. These powder particles might agglomerate with other particles, depending on the temperature in the hot jet and proximity to the laser beam. If these particles become as large as the molten droplets described above, they are also difficult to be transported by the gas flow.

A well-designed gas flow:

- can efficiently remove the soot which can no longer spread in the process chamber, reach the laser window or constitute a constant threat for the laser to expose through it.
- and along with a good scanning strategy, can also help circumvent the creation of the ejecta and contact with the laser beam.

## Build quality difference between a GE Additive Concept Laser M2 (generations prior to Series 4) machine and a Concept Laser M2 Series 4 machine



Left: GE Additive Concept Laser M2 (generations prior to Series 4)

Right: GE Additive Concept Laser M2 Series 4

**Figure 2:** Sample build job to visually investigate laser-soot interaction. Image credit: GE Additive

Figure 2 shows two visual inspections of sample build jobs printed using a GE Additive Concept Laser M2 (generations prior to Series 4) machine (left) and with a GE Additive Concept Laser M2 Series 4 machine (right).

On the left, the pin in the center clearly shows a rougher surface, compared to the counterpart printed on a GE Additive Concept Laser M2 Series 4 machine. This test build job - not recommended in a production environment - was set up to focus on scanning order and to evaluate the influence of downwind scanning (blue-dotted marked region), that is, the second laser prints through the soot of the first laser.

In the red-dotted marked region, the upstream part has finished printing and no further laser-soot interaction influences the printing process of the cylinder.

As anticipated, when setting up the test print, surface roughness is increased on the Concept Laser M2 machine (generations prior to Series 4) machine - as seen in the blue-dotted region, compared to the red-dotted region. Although scanning downwind on the Concept Laser M2 Series 4 machine, the surface roughness in the downwind region - at first glance - look very similar.

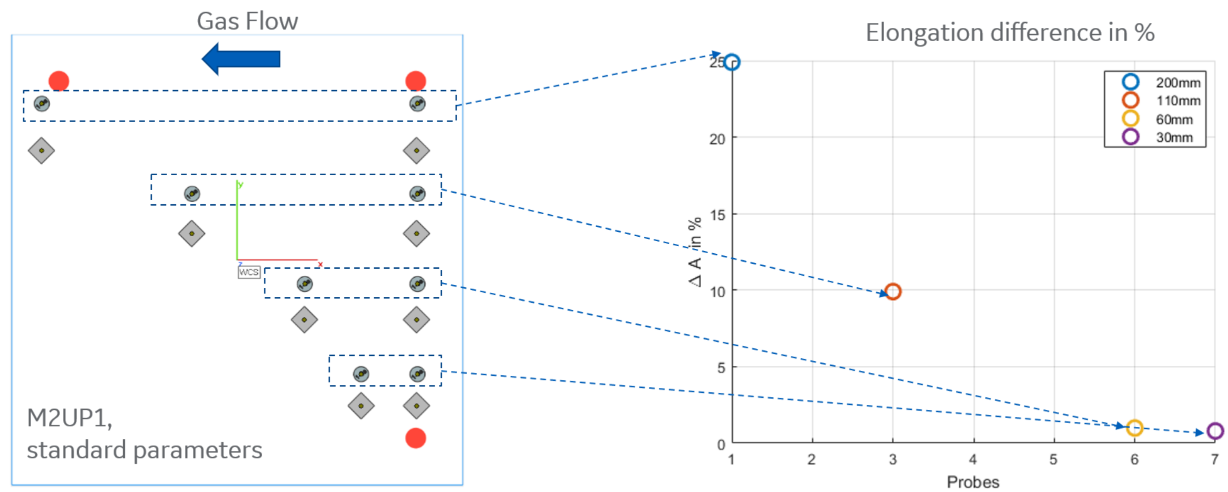



**Figure 3:** Sample build job to investigate laser-soot interaction regarding the mechanical properties of stainless-steel samples. Left: build plate set-up. Right: Elongation difference between reference sample on the right and corresponding sample on the left. Image credit: GE Additive

However, there are cases where no apparent differences are visible when looking just at the surface conditions. Mechanical testing reveals that these samples were printed under the influence of laser-soot interaction.

As shown in Figure 3 (right) elastic elongation is reduced by up to 25% when the laser must constantly pass through the soot - that is - the elongation of the sample on the right of the build plate is up to 25% higher compared to that on the left. It might seem contradictory that samples far away from the soot-source are most impacted by laser-soot interaction. The answer can be found in the average soot pattern that is formed in the flow direction and their characteristics close to the melt pool.

The hot plume first rises by a few centimeters into the process chamber before being transported away and cooled down. This enables the second laser to print "under" the rising plume without interacting with the condensing soot particles. Depending on the gas flow speed, the rising soot particles from the melt pool that have not yet been condensed (and blackened, shown by internal studies and a study by M. J. Matthews et al [9]), constitute a lesser threat to the impacting laser beam.

If a bad gas flow design is in place, namely an inhomogeneous flow field over the build plate or low flow velocities, then the soot patches hover longer and larger over the build plate, further increasing soot concentration, which increases the possibility of the laser power being attenuated, and subsequently impairing the printing process. The better the gas flow design, the thinner the soot plumes that could possibly interfere with the laser path.

This underlines that the Concept Laser M2 (generations prior to Series 4) machine delivered good part quality, when the printing process was less extreme - namely where the laser paths were clearly separated from each other or lower laser power was used to mitigate the risk of soot interference.

## Continuous improvement in gas flow design

Over the past few years GE Additive has been investigating the physics and the impact on the quality and productivity as part of the evolution of its machine portfolio. Integral to that work has been to continuously improve gas flow design to achieve the best part quality.

In this section, we present the evolution of the Concept Laser M2 machine applying growing comprehension of the underlying melt pool physics and the associated transport issues.

Using GE Additive's Concept Laser M2 (generations prior to Series 4, before 2018) machine and a M2 Series 4 (released 2018) machine we demonstrate in more detail what has changed with respect to the gas flow design and why. Further improvements, released on the M2 Series 5 in 2020 are mentioned in the conclusion.

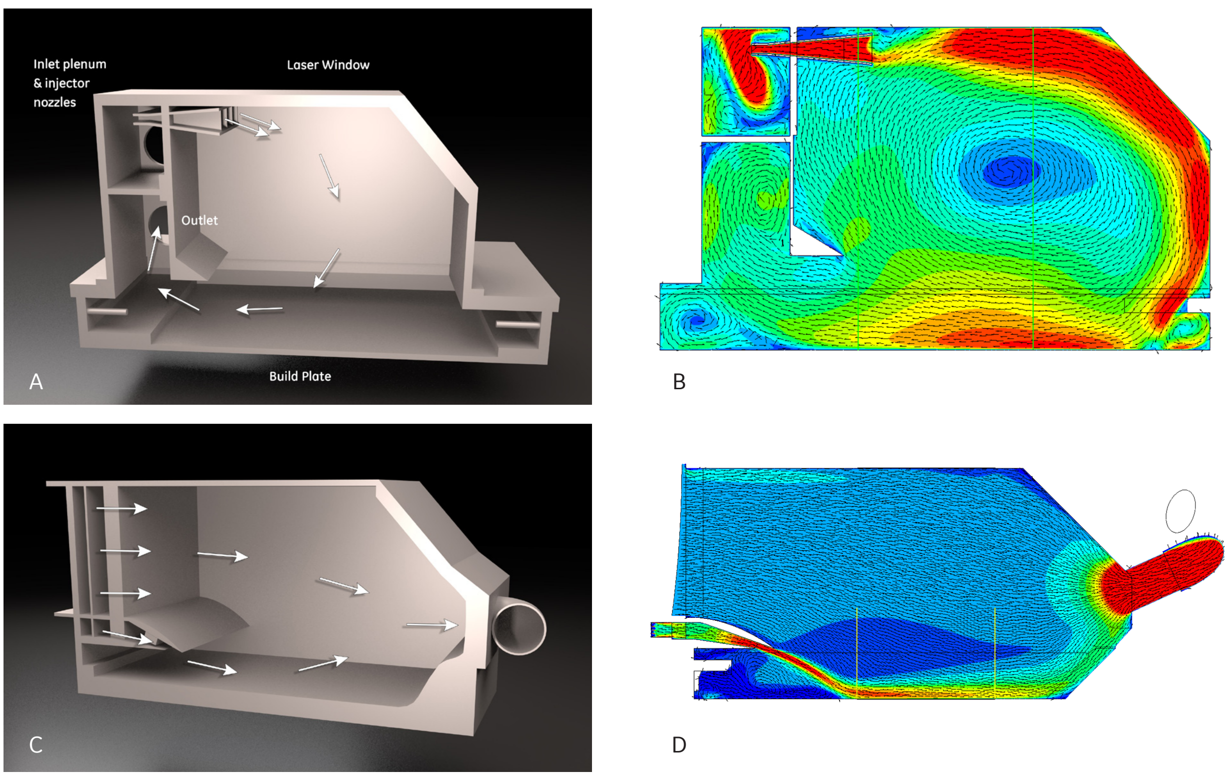



**Figure 4:** Flow concepts of GE Additive Concept Laser M2 (generations prior to Series 4) machine, (a) and b), and GE Additive Concept Laser M2 Series 4 machine, (c) and d)). Image credit: GE Additive

The GE Additive Concept Laser M2 (generations prior to Series 4) machine employed a gas flow design that served two major purposes - as demonstrated in Figure 4 a) and b) (top).

Firstly, to flush the laser window to prevent soot from contaminating it. Secondly, to transport any ejecta from the build plate to the process chamber outlet.

Since the understanding of melt pool physics and parameter development was previously not as advanced as it is today, this robust system was deemed satisfactory in order to provide a stable print.

With increased understanding of the physics involved and further parameter development, with respect to increasing build rates, it became evident that the recirculation region in the center of the process chamber creates a potential trap for soot, which would consequently interact with the laser beams. Especially in the center of the build plate where the recirculation region sits directly above it, in high-energy-density cases, the soot plume can rise into the recirculation region, where it becomes trapped.

The complex streamline curvature caused by the deflection of the flow makes it difficult to obtain homogenous velocity distribution over the entire build plate. Local powder pick-up might follow depending on pump speed and unfavorable flow structures under the re-coater could evolve.

Nevertheless, the machine delivered robust results, but in order to further decrease the surface roughness and enhance reproducibility, a new design was developed.

From the GE Additive Concept Laser M2 (generations prior to Series 4) machine design it was known that a recirculation zone is formed and that the flow distribution varied by +/- 30% (which is comparable to what competitors still deliver today).

Developing a two-section flow concept to provide a more complete and detailed understanding of the physics, GE Additive partnered with flow analysis and optimization experts at GE Global Research, resulting in a design shown in Figure 4 (c) and (d).

In order to tackle these two main issues a new flow concept has been conceived:

- As a first design step, the flow direction in the process chamber was uniformly set from right to left (when viewed through the process chamber window) to eliminate counter-directed flow causing recirculation.
- The second step, for the known soot behavior, the required velocities were evaluated and consequently, the process chamber has been separated into two parts.

The design steps were constantly iterated, that is, the design flow went from numerical simulations to the mechanical design, then to the experimental results resulting in proposed changes in the design, which were tackled again by numerical simulation.

After a few cycles, the current design was obtained. The experimental results were obtained in tailored test rigs and labs, as well as in machine prototypes. Flow measurement devices were developed to reliably quantify the gas flow and to assist the development of the new gas flow design effectively.

The upper part of the process chamber - further away from the build plate - requires a low gas flow speed (in the order of 1 m/s), but homogeneous flow distribution since the soot-plume speed is rather low, too. Instead the focus is set to keep the laser window clean and prevent recirculation zones in the process chamber. Lower velocities in the upper flow lead to recirculation zones and need to be avoided at all costs.

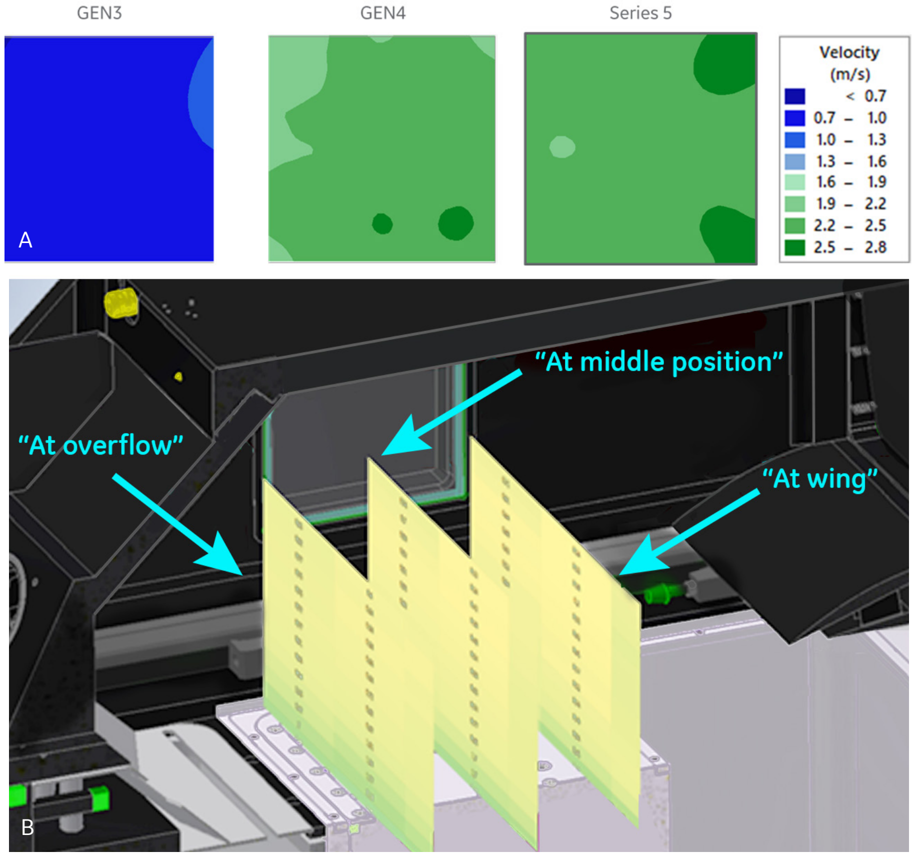



**Figure 5:** a) Evolution of build plate velocity from Gen 3 to Series 5 (left to right). A significant improvement of the flow field quality is observed.

b) Experimental results of gas flow measurements in process chamber. Slices show homogenous velocity distribution in the process chamber and over the build plate.

Image credit: GE Additive

The lower part of the process chamber is flushed with a high-speed jet, which predominantly tackles the soot plume above the build plate to carry the soot - as efficiently as possible - away from the laser beam path. The goal is to achieve permanent soot removal and to keep the average soot concentration as low as possible.

The thickness of the lower jet is important due to the high momentum of the soot plume. A very thin jet has nearly no impact on the soot plume and the flow in the upper part of the process chamber, away from the build plate, which is not primarily designed to move high momentum particles, has then the task burden to deflect the plume.

Figure 5a depicts the evolution of the build plate velocity distribution, which is mainly driven by the lower jet, from Gen 3 to Series 5 today. The latest machines show considerably higher flow velocities compared to machines prior to Gen 4, which are needed to effectively evacuate the soot and spatter of the melting process.

The homogenous flow velocity of the upper and lower flow in the streamwise direction is demonstrated via experimental results in Figure 5. The homogenous flow field enables consistent scan strategies that are characterized by a low risk of soot-plume interference over the entire build plate - leading to low part-to-part variation, which is independent of the location on the build plate.

Figure 6 depicts the flow field of the simulation and observes that the soot plume, caused by a high energy density laser parameter, is transported downstream, effectively, without reaching the upper part of the process chamber.

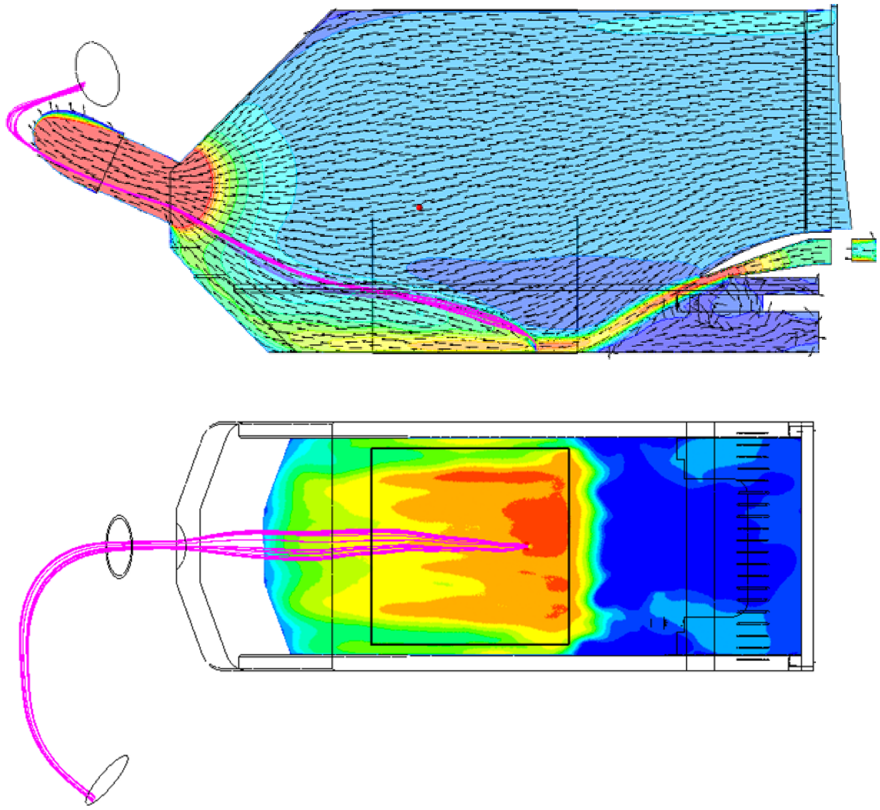


**Figure 6:** Streamlines of soot particles and velocity distributions in a Concept Laser M2 Series 4 machine flow environment. Top: side view, bottom: top view. Image credit: GE Additive

This worst-case scenario shows that in a GE Additive Concept Laser M2 Series 4 machine configuration, the plume does not rise above the lower flow limit, but is deflected and carried away to the exit, before the soot reaches the upper regions of the process chamber.

## Conclusion

Through thorough screening of the origin and behavior of soot and spatter originating from the melt pool we know that the gas flow in our laser machines must fulfill a full stack of requirements to transport the ejecta away from the build plate as efficiently as possible.

GE Additive continues to constantly research melt pool physics and the gas flow system to further optimize its machine portfolio with respect to higher productivity and reproducibility of part quality - within the framework of serial production.

The well-designed gas flow and efficient soot evacuation features on the new M2 Series 5, have been complemented with an aerodynamic favorable recoater design, a velocity control method minimizing machine to machine variation and more. It delivers outstanding part quality under extreme manufacturing situations, with respect to scanning strategies and build rates.

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