Whitepaper: Understanding powderbed physics to push the boundaries of metal AM with the MetalFab™420K

Additive Industries b.v.
Achtseweg Zuid 155,
5651 GW Eindhoven,
The Netherlands
T: +31 (0)40 2180660

Understanding powderbed physics to push the boundaries of metal AM with the MetalFab™ 420K

This whitepaper demonstrates how Additive Industries' ensure in-depth understanding of particle pickup speed in relation to the higher gas flow rates required when scaling up in build size and applied laser power - critical for controlled process conditions. By showing excellent agreement between model and experiment, a solid foundation has been developed to keep up with the rapid development of new materials and the demand for higher build rates. This fundamental knowledge has been used to develop the gas flow design of the MetalFab 420K. Results show a homogeneous flow field with high velocities, with these high velocities being strategically located as close to the process plane as possible whilst maintaining an undisturbed powderbed.

Introduction

Inert shielding gas flow is a crucial element in process control to achieve the desired part quality and consistency across the entire build area in metal Additive Manufacturing. This challenge scales with the system's chamber size, number of lasers, and the applied laser power, with these factors influencing the rate with which process emissions are produced. The MetalFab 420K employs the power of 4 × 1 kW lasers and to ensure consistency, accuracy and predictable part quality, even for complex geometries, shielding gas flow plays a significant role in ensuring that the build chamber remains free from spatter and condensate fumes during printing.

Shielding gas flow

Apart from countering beam attenuation and redeposition of cold and hot ejections, the gas flow influences the process through convective cooling of the melt pool. Beam attenuation occurs when the laser beam interferes with process by-products absorbing part of the laser beam's energy which leads to a change in melt pool dynamics. Redeposition could lead to lack-of-fusion defects and out-of-plane growth. Ensuring flow homogeneity across the build platform enables a stable, repeatable process. Literature confirms that increasing the inert gas flows indubitable leads to an increase in part quality.

By increasing the inert gas flow, the time scales involved with spatter and condensate removal decrease allowing for an increase in laser power, scanning speed, and subsequently higher productivity. Nevertheless, there is an upper limit to the amount of shielding gas flow one can apply: the Particle Pickup Speed (PPS) – the velocity required to resuspend (blowing away) a particle initially at rest on the bottom of the build chamber. When this speed is reached powder particles will be entrained in the shielding gas flow and the powderbed will be disturbed. A disturbed powder bed will lead to a variety of defects in your part and in this paper we explore the limitations of the shielding gas flow, strengthening our knowledge to employ it's power to the fullest.

Physics of the powderbed

When the Particle Pickup Speed (PPS) is reached over the powderbed, the powderbed will be disturbed and "virgin" powder particles will be entrained in the process gas flow, leading to a significant decrease in part quality. PPS is also known as the saltation velocity and varies with particle density, diameter, sphericity and the type of fluid medium. There have been several models developed to predict the PPS for a variety of materials and particle diameters in different fluid media and one of the more accurate models (when comparing the model with published experimental results) is the empirical model of Kalman et al. [1-3]. This empirical model is based on a large variety of experimental results, defining three

Additive Industries
B.V. Headquarters,
Eindhoven,
The Netherlands
T: +31 (0)40 2180660

Additive Industries
North America, Inc.
Camarillo, United
States of America
T: +1 805 530 6080

zones (based on particle diameter) by establishing simple relationships between the Reynolds and Archimedes numbers. The Reynolds number is a dimensionless number describing the ratio of inertial forces with respect to viscous forces. The Archimedes number is also a dimensionless number used to describe the ratio of a buoyancy force due to a difference in density and viscous forces.

The first zone of the three zones described by the model, is assigned to larger particles. In the second zone, cohesion forces start to affect the pickup velocity. And the third zone is valid for fine and very cohesive powders. Figure 1 shows the results of applying this particular model by Kalman et al. to solid aluminium and IN718 particles with argon as the fluid medium. The curve shows a minimum in the PPS when it shifts from zone I to II. It comes to no surprise that most commercially available powders are in that same range of particle diameters near the minimum of the PPS. If they were not, they would be very difficult to transport or handle (powder spreading).

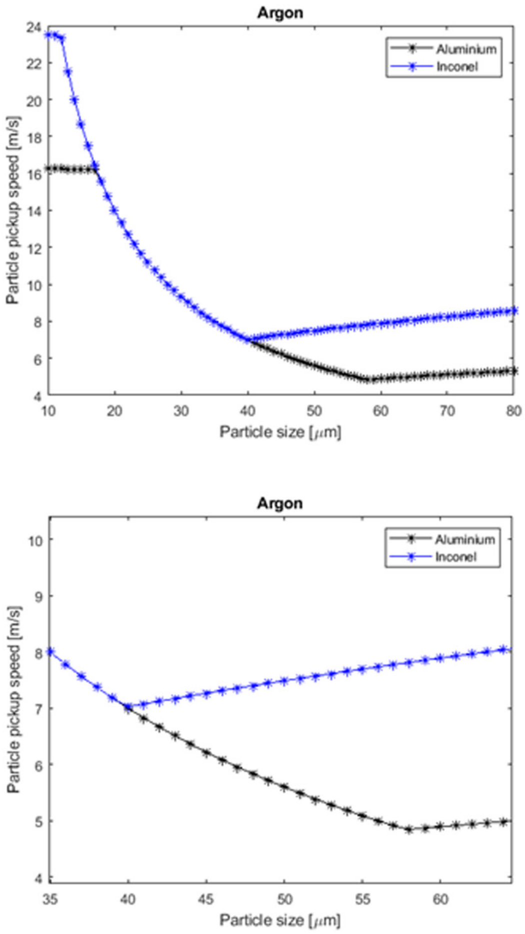


Figure 1 – Particle pickup speed [m/s] for Aluminium and Inconel in argon as a function of particle diameter [μm]

All MetalFab machines offer the possibility to use nitrogen instead of argon - this is not desirable for all applied metal powders due to the chemical reactions that can take place between nitrogen and particular metal alloys (for instance titanium) - but Figure 2 shows the PPS if these two materials were transported in nitrogen. The figures clearly show that the critical velocities involved are higher than those involved when using argon as the fluid medium. The focus in this white paper will be on using argon as inert shielding gas.

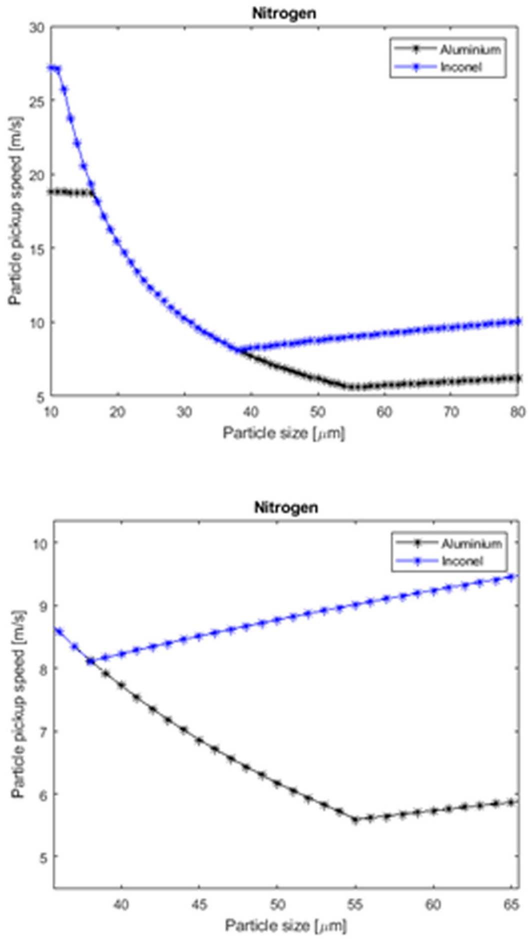


Figure 2 – Particle pickup speed [m/s] for Aluminium and Inconel in nitrogen as a function of particle diameter [μm]

Experimental test setup

Theory only has value if it can be validated by experiments. A dedicated experimental setup has been designed and constructed to put this particular theory to the test. The setup consists of a long duct (to ensure a developed flow) with a test chamber holding powder samples in line with

Additive Industries
B.V. Headquarters,
Eindhoven,
The Netherlands
T: +31 (0)40 2180660

Additive Industries
North America, Inc.
Camarillo, United
States of America
T: +1 805 530 6080

the bottom of the duct. A variety of sample trays allow for examining the influence of different depths of powder layers, examining the influence of powder layer interaction. Pitot tubes and a movable hot wire probe are employed to determine the flow profile imposed on the powder layer. A camera is installed to capture the pickup of the powder particles. The setup is able to run on both argon and nitrogen.

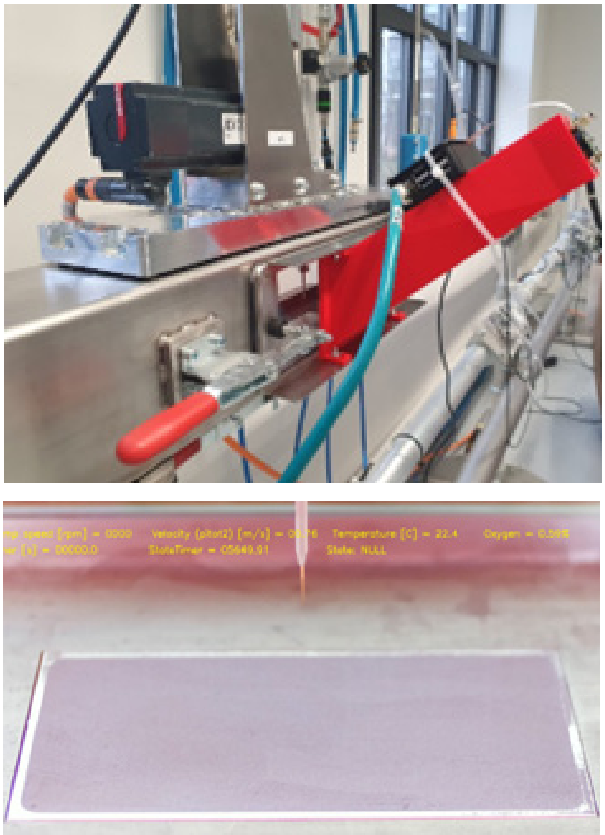


Figure 3 – A camera has been mountend on the test section to capture the conditions of particle pickup (left), a screenshot with all necessary data is shown (right)

By increasing the velocity of the fluid medium with small fixed increments, the particle pickup speed could be determined for a variety of metal powders. A hot wire probe (calibrated in the same setup with a pitot tube) was used to measure the velocity profile in the test section. To ensure that the accuracy of the measured flowprofile was sufficient to capture the boundary layer near the wall, numerical simulation of the setup were conducted to determine the position of the boundary layer.

The boundary layer is a thin layer of fluid formed on the surface which interacts with the flow (the wall of the tube). The thickness of this layer grows along the length of the surface and depends on the characteristics of the fluid medium, the velocity, and on the surface roughness of the tube itself.

As can be seen in figure 4, excellent agreement was found between the numerical simulation and the flow profile measured by a hot wire probe in the test setup, strengthening the knowledge of the imposed conditions on the powder layer present at the bottom of the experimental setup.

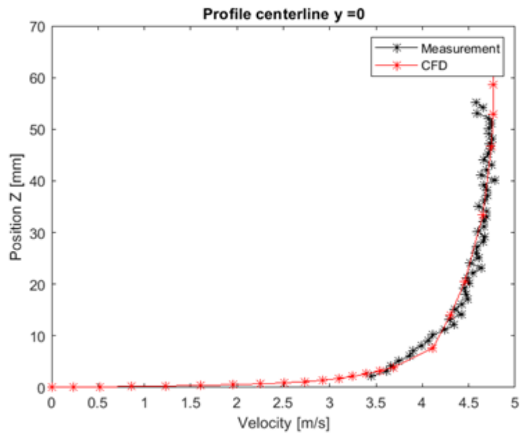


Figure 4 – A velocity profile in the centre of the tube, a comparison between numerical and experimental results

Particle pickup speed results

The Particle Pickup Speed (PPS) has been determined for a variety of powders, with a focus on the powders with the smallest density. A selection of these results are presented in figure 5. The coloured error bars show the experimental result within an accuracy of 0.2 [m/s] and the black stars show the PPS based on the empirical model of Kalman et al. These results emphasize the good agreement of this model with the conducted experiments. The trends described in literature (fluid density, particle density, sphericity) were all examined and verified.

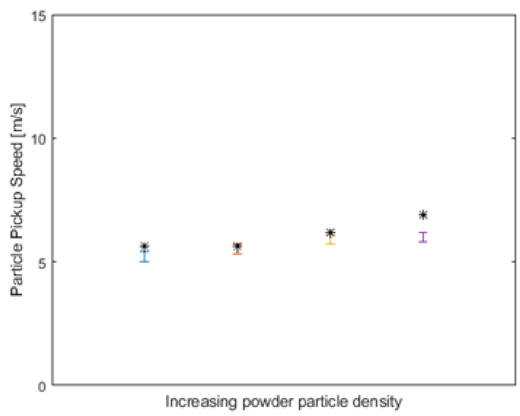


Figure 5 – Comparison between the empirical model by Kalman et al. and the PPS determined by our inhouse experimental setup

Additive Industries
B.V. Headquarters,
Eindhoven,
The Netherlands
T: +31 (0)40 2180660

Additive Industries
North America, Inc.
Camarillo, United
States of America
T: +1 805 530 6080

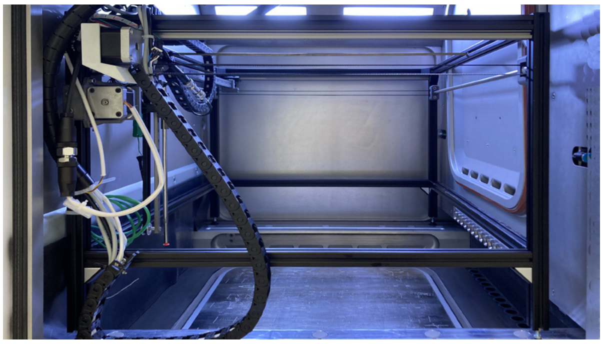
MetalFab 420K – redefining boundaries towards high productivity

To accelerate the application of metal AM to a level of high productivity with high quality, the MetalFab 420K has been developed. Amongst other innovative features, this machine employs the energy of 4 × 1 kW lasers to facilitate the market's need for a higher productivity system. This significant increase in laser power will undoubtedly lead to an increase in spatter particles as well as the size of these particles, and their ejection velocity, therefore to ensure stable process control, the flowrate (in respect to the MetalFab G2 which employs 4 × 500 W lasers) has been doubled to 320 [Nm3/h]. Doubling the flowrate, it is important to maintain an undisturbed powderbed.

Based on the knowledge acquired in relation to the PPS, the requirements for the process gas flow velocity have been set as follows:

$v < 4$ [m/s] at $h = 10 - 20$ [mm]
$v < 3$ [m/s] at $h = 2 - 10$ [mm]

The overall velocity v [m/s] should not be larger than 3 [m/s] at a height of 2 – 10 [mm] above the process plane. Between h = 10 and 20 [mm], the overall velocity should be smaller than 4 [m/s]. At heights larger than 20 [mm], the overall velocity can be as high as possible.
By developing a new primary manifold and nozzle, a consistent, homogeneous flow field could be produced. To ensure all set velocity requirements were met, a 3D measuring gantry has been employed with thermal anemometry being the most suitable measurement technique available for measuring flow velocity. By using a customized measuring gantry which fits the build chamber of the MetalFab 420K exactly and employs calibrated hot wire probes, the flow field could be analysed. The 1D hot wire probes (5 μm wire diameter to ensure fast response – measurement frequency of 10 kHz) were calibrated for argon, and measure the effective velocity which summarizes all contributions of the different velocity vectors.



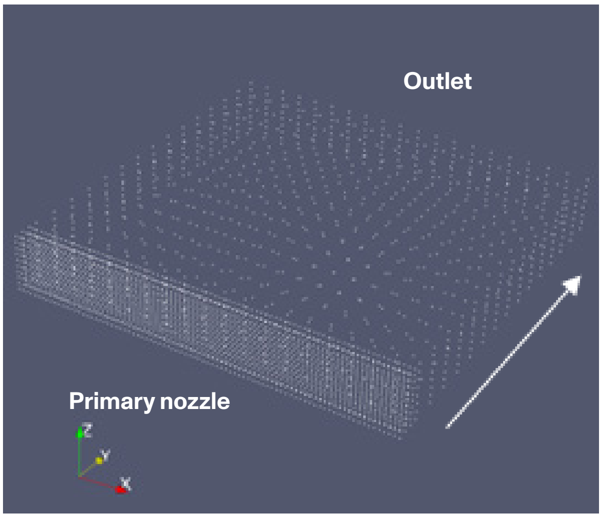


Figure 6 – Measurement gantry, which allows for automated flow field 1D velocity measurements in x, y and z-direction, and the chosen measurement domain

The measurement domain was divided into two regions - the first, just at the beginning of the build plate and with a small spatial resolution and a second one starting at 30 [mm] depth of the build plate going towards the back with a coarser spatial resolution (right side of figure 6). The results can be seen in figure 7.

Measurement time was set to 1 second, leading to a local average value of 10.000 separate measurements. The standard deviation was also stored in the data output and since this standard deviation is a combination of turbulence effects and measurement errors in itself, it has not been used in the overall data post processing, since it will be impossible to connect any physical or metrological conclusion to them. The results in figure 7 show a homogeneous flow across the width of the build plate as well as from the front to the back.

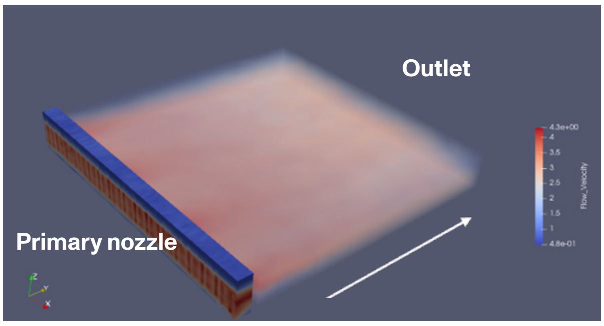


Figure 7 – Measurement results showing the flow field (coloration is based on local effective velocity [m/s]) from front to back over the build plate area of the MetalFab420K.

Additive Industries
B.V. Headquarters,
Eindhoven,
The Netherlands
T: +31 (0)40 2180660

Additive Industries
North America, Inc.
Camarillo, United
States of America
T: +1 805 530 6080

To further examine the flow, local (x and y position) flow profiles were examined. The x-position refers to the width of build plate, while the y-position describes the depth [mm]. The dimensions of the build plate surface are 420 x 420 [mm] so the position (0,0) refers to the most left position at the front of the build plate. Figure 8 shows the flow profiles at the front edge of the build plate (y=0 [mm]) as well as at y = 20 [mm].

The results presented in figure 8 demonstrate the homogeneity across the width of the build plate. The flow profiles almost seem to overlap one another, and based on the knowledge acquired by the windtunnel setup and literature, two flow velocity requirements were set to avoid Particle Pickup Speed to be reached.

$v < 4$ [m/s] at $z = 10 - 20$ [mm]
$v < 3$ [m/s] at $z = 2 - 10$ [mm]

To avoid collision with the build plate, the probe was located 7 [mm] above the build plate. The velocities were examined at z = 3 and 13 [mm] with figure 9 showing the results for y = 20 [mm]. Of course, many locations were examined which are not shown in this paper and all profiles proved to be within the set specifications. In addition, tests have been conducted with aluminum powder in the build chamber to validate these requirements - as long as the PPS was not reached, the powderbed remained undisturbed.

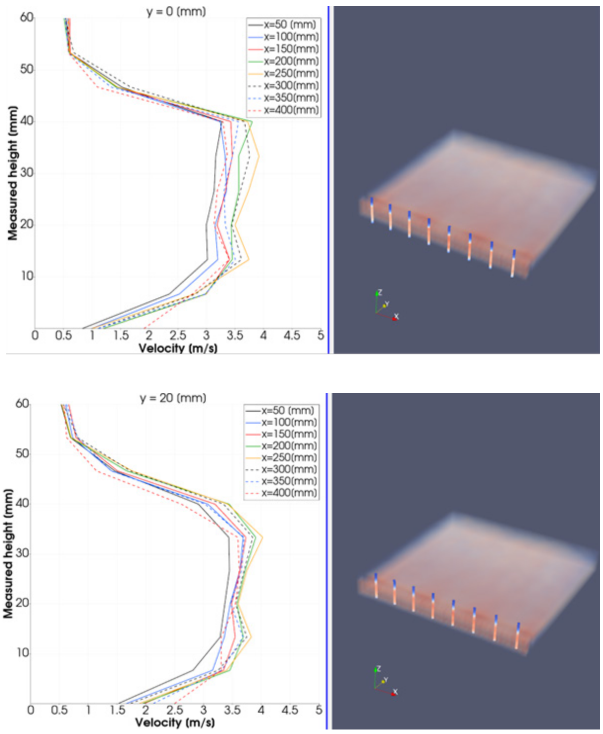


Figure 8 – Measurement results showing the flow profiles across the width of the buildplate just after the nozzle, at the front. The probe was located 7 [mm] above the build plate (corresponding with z = 0 [mm] in the graph).

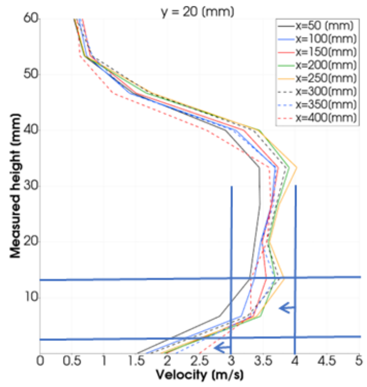


Figure 9 – Flow profiles were used to determine if the specified requirements to avoid the Particle Pickup Speed (PPS) for Aluminium were met.

To further examine the flow field of the MetalFab 420K, the flow profiles going from the front to the back of the build plate were analysed. Since it is believed that close to the process plane the shielding gas flow plays a significant role in contaminant control, the profiles were examined at h = 10 [mm] (corresponding to z = 3 [mm] of the measurement domain) and h = 25 [mm]. The measured flow profiles can be seen in figure 10 and again, all profiles are located very close together, underlining the stability and homogeneity of the flow. Closer to the build plate (h = 10 [mm]) it is clear that at the front of the area the flow velocities are slightly smaller.

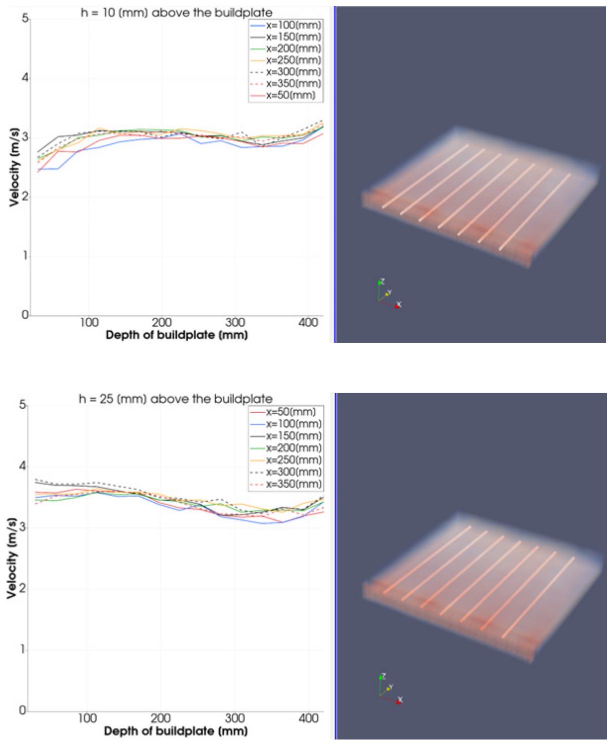


Figure 10 – Measured flow profiles from front to back (y = 30 [mm] to y = 420 [mm]), at actual height h = 10 [mm] and h = 25 [mm]. The right figure shows the location of these line profiles in regard to the entire build plate.

Additive Industries
B.V. Headquarters,
Eindhoven,
The Netherlands
T: +31 (0)40 2180660

Additive Industries
North America, Inc.
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States of America
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After 100 [mm], the flow is developed and velocities are constant across the remainder of the depth of the build plate. Towards the outlet there is a small rise in velocity visible which is understandable due to the size of the outflow surface in relation to the primary and secondary nozzle outflow surfaces.

At h=10 [mm] the average velocity of the seven flow profiles is 2,92 [m/s], the minimum velocity is 2,41 [m/s] and the maximum velocity is 3,07 [m/s] with a maximum deviation of 17.5% of the average value. At h=25 [mm] the average velocity of the seven flow profiles is 3,38 [m/s], the minimum velocity is 3,09 [m/s] and the maximum velocity is 3,63 [m/s] with a maximum deviation of 8,6 % of the average value.

Taking turbulence effects and measurement errors into account, these are very impressive results that demonstrate a stable, homogeneous flow field across the entire process plane, with high velocities which do not disturb the powderbed. To ensure the repeatability of this flow field, multiple measurements have been executed. A comparison of some of the collected data can be seen in figure 11. - these profiles show excellent agreement between separate measurements and any deviations are well within 10% of the local absolute values.

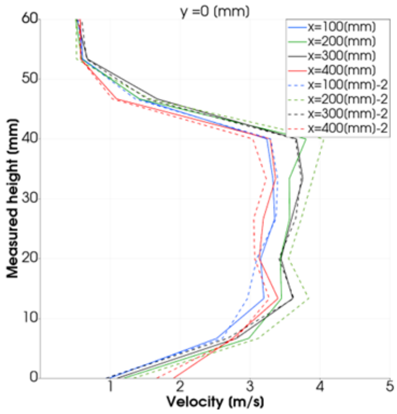

Figure 11 – To examine repeatability multiple flow measurements were executed and flow profiles compared. The dashed curves show the results of one of these repetitive measurements.

Flow field homogeneity

In the previous sections, flow profiles have been examined at specific locations. To ensure homogeneous flow across the entire build plate area, full field measurements have also been examined. The flow field has been examined at h = 20 [mm] and h = 25 [mm] which corresponds to the measured height of 13 [mm] and 18 [mm]. In this area the velocities are high, and due to the development of the flow (expansion of individual turbulent jets) it is the most suitable position to examine homogeneity. Homogeneity can be described as the lack of variation, and it is believed that if the gas flow velocity does not vary much across the process plane, the variation in part quality will also be small.

The flow field velocity at h = 20 [mm] can be seen in figure 12. In this plane, 549 measurement points are located (249 in region 1 – at the front, and 300 in region 2). As can be expected, the highest velocities can be seen in the front, just after the nozzle and due to natural expansion the absolute local velocity decreases.

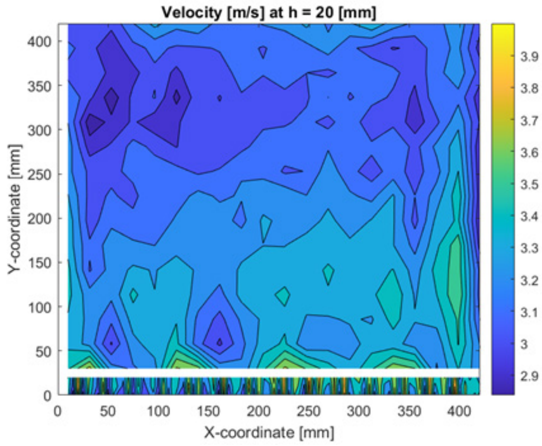

Figure 12 – Absolute velocities at h = 20 [mm] above the buildplate – the measurement domain consists of 549 data points.

To determine the variation across this plane, the mean velocity has been calculated. This mean velocity was then used to determine the local deviation of that velocity across the plane with the results shown in figure 13.

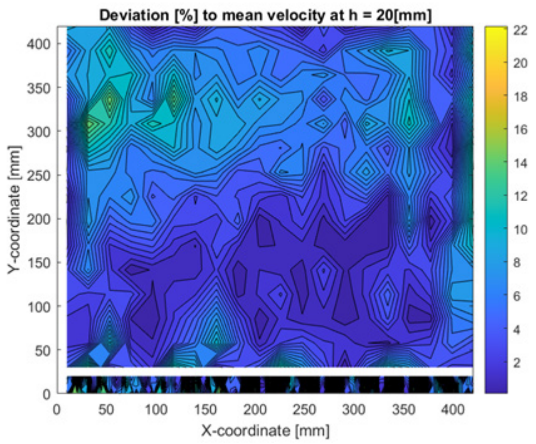

Figure 13 – Deviation [%] in relation to the mean velocity [m/s] across the entire measurement plane at h = 20 [mm] above the buildplate – the measurement domain consists of 549 data points.

Largest deviations were found at the front of the buildplate, which corresponds with the higher velocities located just after the nozzle. The percentage of data points which showed a deviation of 15% or higher was 7%. In total, 81% of the data points showed a deviation of 10% or less.

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B.V. Headquarters,
Eindhoven,
The Netherlands
T: +31 (0)40 2180660

Additive Industries
North America, Inc.
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States of America
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The same analysis has been executed for h = 25 [mm] above the process plane and the results are presented in figure 14. In this analysis (at h = 25 [mm]), 84% of all data points showed a deviation in regard to the overall mean velocity of 10% or less.

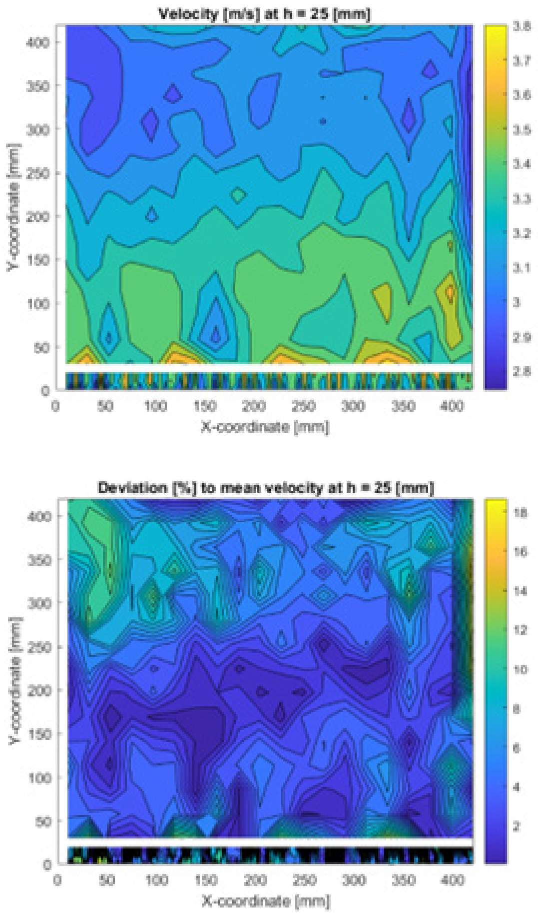

Figure 14 – Velocity [m/s] and deviation [%] in relation to the mean velocity [m/s] across the entire measurement plane at h = 25 [mm] above the buildplate – the measurement domain consists of 549 data points.

Summary and outlook

In this paper we have explored the limitations of the shielding gas flow, strengthening our knowledge to employ it's power to the fullest. With regards to the physics of both the separate powder particles as well as the powderbed as a whole, a limit of the shielding gas flow is to be found in the particle pickup speed. We were able to experimentally determine this speed which was in line with literature and the work put forward by others.

Subsequently, this knowledge was directly implemented during the development of the MetalFab420K. Doubling the flowrate, increasing flow velocities, optimizing velocity variation at critical locations above the process plane, and ensuring an undisturbed powderbed. Understanding the physics of the powderbed in relation with shielding gas flow and energy input, will play an essential role in moving towards increasing part quality and build rates in all Additive Industries MetalFab systems.

The MetalFab 420K has greatly benefitted from this work, underpinning its new gas flow design and unlocking process parameters in materials such as Aluminium alloy AlSi10Mg and Nickel alloy IN718 with process productivity rates of up to 3 x that of 500W laser systems.

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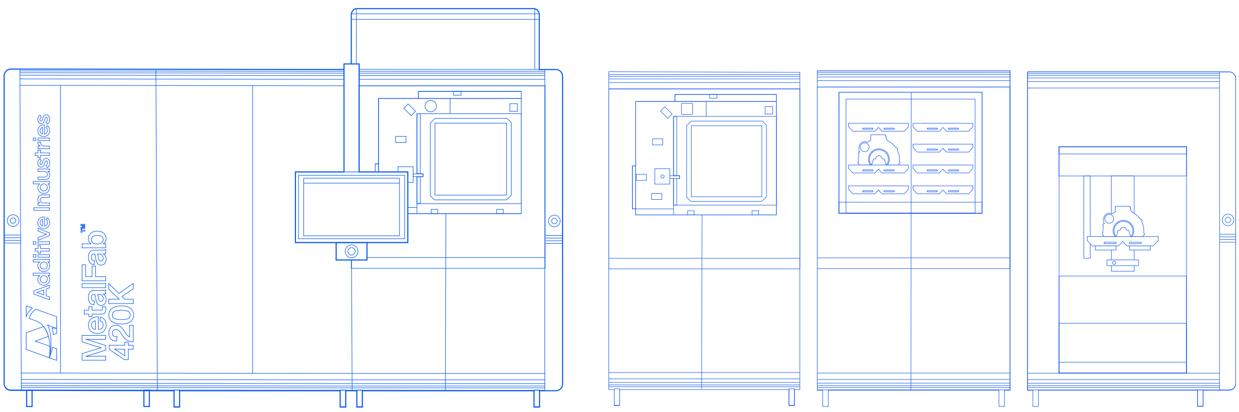

Additive Industries
B.V. Headquarters,
Eindhoven,
The Netherlands
T: +31 (0)40 2180660

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North America, Inc.
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States of America
T: +1 805 530 6080

White paper

At Additive Industries, our objective is the success of our customers in achieving the lowest cost per part at market leading quality.

We pride ourselves on our flexibility to work with our MetalFab users in achieving their industrial goals.

To find out more, contact us at:
info@additiveindustries.com

www.additiveindustries.com

Contact details

Additive Industries b.v.
Achtseweg Zuid 155, 5651 GW Eindhoven,
The Netherlands
P.O. Box 30160, 5600 GA Eindhoven,
The Netherlands
T: +31 (0)40 2180660

Additive Industries North America, Inc.
Process and Applicati ons Development Center
1250 Avenida Acaso, Unit H, Camarillo, CA 93012,
United States of America
T: +1 805 530 6080