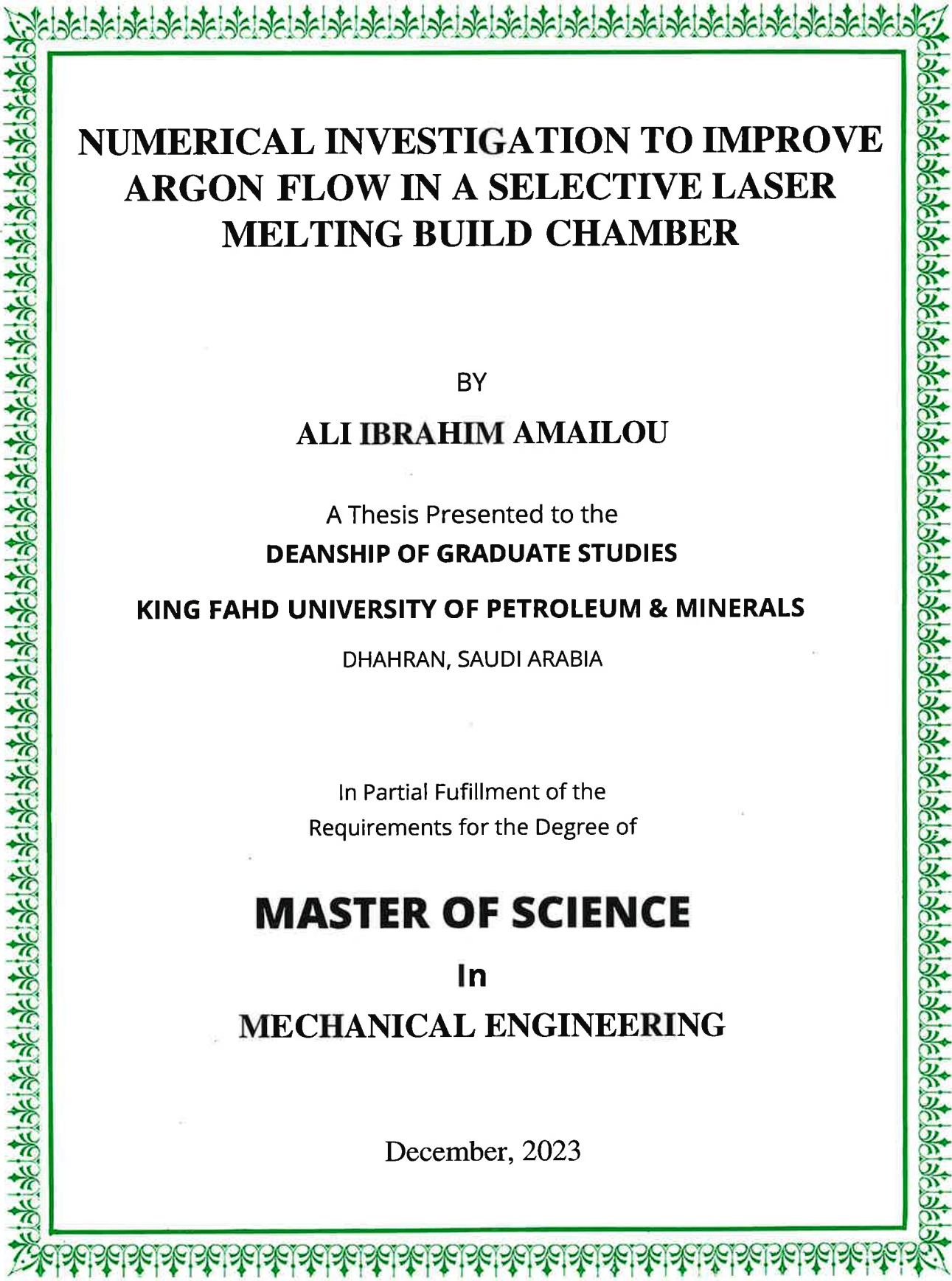




NUMERICAL INVESTIGATION TO IMPROVE ARGON FLOW IN A SELECTIVE LASER MELTING BUILD CHAMBER

BY

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A Thesis Presented to the
DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE
In
MECHANICAL ENGINEERING

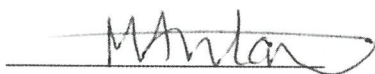
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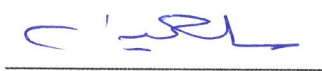
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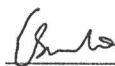
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ACKNOWLEDGMENTS

I would like to express my deepest gratitude to my advisor Dr. Awad Alquaity for his unwavering support, guidance, and expertise throughout the course of my research. His insightful feedback and encouragement have been invaluable in shaping the trajectory of this work.

I extend my sincere appreciation to the members of my research committee Dr. Usman Ali and Dr. Muhammad Hawwa for their constructive criticism and valuable suggestions. Their diverse perspectives enriched the quality of this thesis.

I am indebted King Fahd University of Petroleum and Minerals for providing me financial support, which made this research possible. Their belief in the importance of this work has been a motivating force.

Heartfelt thanks go to my colleagues and peers who provided a stimulating academic environment and shared their knowledge generously. The collaborative spirit within The Mechanical Engineering Department has been instrumental in enhancing the depth and scope of my research.

I want to express my gratitude to my family for their unwavering support and understanding during this challenging journey. Their love and encouragement provided the foundation upon which I could build my academic pursuits.

Finally, to my friends who stood by me, offering encouragement, laughter, and a welcome distraction when needed – your friendship has been a cherished aspect of my academic life.

This work is a testament to the collective efforts of those who believed in and contributed to its realization.

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NOMENCLATURE

$\vec{v}$: Velocity.

ρ : Density.

p : Static pressure.

μ : Dynamic viscosity.

F_D : Drag force per unit mass.

ρ_p : Particle density.

C_D : Drag coefficient for smooth spatter.

d_p : Particle diameter.

b_1, b_2 and b_3 are constants provided by Morsi and Alexander [19].

d_v is diameter variation between the nozzle and the next.

d_{n13} is the last nozzle diameter.

d_{n1} is the first nozzle diameter.

CFD: Computational Fluid Dynamics.

DPM: Discrete Phase Model.

ABSTRACT

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Thesis Title : NUMERICAL INVESTIGATION TO IMPROVE ARGON FLOW IN A
SELECTIVE LASER MELTING BUILD CHAMBER

Major Field : Mechanical Engineering

Date of Degree : December 2023

The presence of spatter particles in selective laser melting (SLM) processes poses significant challenges, potentially impacting the quality of the final parts produced. Despite efforts to redirect these particles away from the build plate using inert gas flow, some resettlement can occur, leading to unexpected variations in the mechanical properties of the components. This study is aimed at improving the efficiency of spatter removal in SLM.

To conduct this investigation, a 3D model of a Renishaw AM250 build chamber was created using SolidWorks and then imported into Ansys Fluent, a commercially available computational fluid dynamics (CFD) software. A mesh independence study was carried out to optimize computational costs and ensure accuracy. Various geometric modifications were introduced to observe their impact on the flow profile within the build chamber, and different combinations of these changes were explored.

The study utilized Discrete Phase Modeling (DPM) to compare the base model with the final design, with the objective of assessing the improvements in the spatter removal process. In the DPM simulations, two materials were studied: AlSi10Mg and SS 316L at different velocities. The inert gas flow rate was kept constant at 250 L/min as used in commercially available build chambers. Three sizes of spatter particles (100, 150, and 200 microns), various ejection angles (10, 35, and 60 degrees), and different locations (left edge, right edge, and center) were also considered for the numerical investigation. This comparative

analysis was conducted to validate and confirm the enhancement in the efficiency of the spatter removal process.

The results of this study provide insights into how geometric modifications and material properties influence spatter removal in SLM processes and contribute to improving the quality of the manufactured components

ملخص الرسالة

الاسم الكامل: علي ابراهيم اميلو

عنوان الرسالة: بحث عددي لتحسين تدفق الأرجون في غرفة بناء الصهر بالليزر الانتقائي

التخصص: الهندسة الميكانيكية

تاريخ الدرجة العلمية: ديسمبر 2023

يفرض وجود جزيئات متناثرة في عمليات الذوبان الانتقائي بالليزر (الذوبان بالليزر الانتقائي) تحديات كبيرة، مما قد يؤثر على جودة الأجزاء النهائية المنتجة. على الرغم من الجهود المبذولة لإعادة توجيه هذه الجزيئات بعيدًا عن لوحة التصميم باستخدام تدفق الغاز الخامل، فمن الممكن أن تحدث بعض عمليات إعادة التوطين، مما يؤدي إلى اختلافات غير متوقعة في الخواص الميكانيكية للمكونات. تهدف هذه الدراسة إلى تحسين كفاءة إزالة الترشيح في الذوبان الانتقائي بالليزر.

لإجراء هذا التحقيق، تم إنشاء نموذج ثلاثي الأبعاد لغرفة بناء Renishaw AM250 باستخدام Solidworks ثم تم استيراده إلى Ansys Fluent، وهو برنامج ديناميكيات الموائع الحسابية المتوفر تجاريًا. تم إجراء دراسة استقلالية الشبكة لتحسين التكاليف الحسابية وضمان الدقة. تم إدخال تعديلات هندسية مختلفة لمراقبة تأثيرها على ملف التدفق داخل غرفة التصميم، وتم استكشاف مجموعات مختلفة من هذه التغييرات.

استخدمت الدراسة نمذجة الطور المنفصل لمقارنة النموذج الأساسي مع التصميم النهائي، بهدف تقييم التحسينات في عملية إزالة التناثر. في محاكاة DPM، تمت دراسة مادتين AlSi10Mg و SS 316L بسرعات مختلفة. تم الحفاظ على معدل تدفق الغاز الخامل ثابتًا عند 250 لترًا في الدقيقة كما هو مستخدم في غرف البناء المتوفرة تجاريًا. تم أيضًا أخذ ثلاثة أحجام من جزيئات الرذاذ (100، 150، و 200 ميكرون)، وزوايا طرد مختلفة (10، 35، و 60 درجة)، ومواقع مختلفة (الحافة اليسرى، والحافة اليمنى، والوسط) في الاعتبار أيضًا للتحقيق العددي. تم إجراء هذا التحليل المقارن للتحقق من صحة وتأكيده التحسين في كفاءة عملية إزالة الترشيح.

توفر نتائج هذه الدراسة نظرة ثاقبة حول كيفية تأثير التعديلات الهندسية وخصائص المواد على إزالة التناثر في عمليات الصهر بالليزر الانتقائية والمساهمة في تحسين جودة المكونات المصنعة.

CHAPTER 1

INTRODUCTION

1.1 Background

Selective Laser Melting (SLM) represents a transformative force in the realm of additive manufacturing, leveraging precision and adaptability that have revolutionized numerous industries. This technique employs powdered metal materials and a high-power laser beam to selectively melt the powder, forming intricate components layer by layer. However, the efficiency of SLM is impeded by the issue of spatter—unwanted droplets of molten material generated during the thermal energy-intensive powder melting process.

To counteract this challenge, the introduction of an inert gas flow into the SLM chamber has proven effective. Inert gases, such as argon or nitrogen, serve dual purposes: they facilitate spatter removal and prevent its deposition onto the powder bed. Despite its widespread use, the optimization and efficiency of this inert gas flow remain underexplored, creating a knowledge gap that this research intends to address.

Inert gases are utilized due to their inherent chemical inertness, which is a result of their complete valence electron shells, rendering them resistant to chemical reactivity. This inherent stability makes inert gases suitable for use in SLM where a non-reactive environment is required to prevent oxidation and other undesirable reactions that could compromise the mechanical properties and surface quality of the final product.

In delving into the role of inert gas flow in SLM, it becomes evident that it not only serves to mitigate the spatter issue but also plays a pivotal role in shaping the quality of the final manufactured product. Beyond spatter removal, the inert gas flow influences thermal gradients, melt pool dynamics, and overall process

stability. The nuanced interplay of these factors necessitates a comprehensive exploration to fully understand and optimize inert gas flow for enhanced additive manufacturing outcomes.

A critical consideration in this exploration is the choice of inert gas. While argon and nitrogen are commonly employed, their distinct characteristics significantly impact the SLM process. Argon, with its higher density, may provide better spatter removal but could introduce challenges in gas flow dynamics. Conversely, nitrogen, with its lower density, might offer improved process stability but could be less effective in spatter removal. Striking a balance is essential for achieving an optimal inert gas flow tailored to the specific requirements of SLM.

To bridge the research gap, this thesis proposes a comprehensive framework for inert gas flow optimization in SLM. The framework involves a systematic investigation into various parameters, including gas flow rate, nozzle design, and chamber geometry. Experimental studies and computational simulations will unravel the intricate interplay of these parameters, providing insights into their individual and collective impacts on inert gas flow efficiency.

Moreover, the research aims to develop a predictive model guiding practitioners in selecting the most suitable inert gas and optimizing its flow for specific SLM applications. By integrating theoretical insights with practical considerations, this model will serve as a valuable tool for advancing the efficiency of inert gas flow in SLM.

In conclusion, this extended exploration into inert gas flow in SLM underscores the intricate dynamics of this critical component in additive manufacturing. Addressing the existing research gap contributes not only to theoretical foundations but also to practical implementation. As the additive manufacturing landscape evolves, a deeper understanding of the nuances associated with SLM processes will undoubtedly propel the field towards new heights of efficiency and innovation.

1.2 Scope of Work

This thesis seeks to investigate the potential enhancements in the geometry of Selective Laser Melting (SLM) chambers with the primary aim of improving the efficiency of inert gas utilization for more effective spatter removal. Notably, the comprehensive exploration of the impact of simple geometric modifications in this context has been lacking in the existing literature, with only limited research having been published on this subject. Consequently, this study endeavors to address this research gap by examining various geometrical alterations, employing commercial Computational Fluid Dynamics (CFD) software for simulation. Upon conducting the simulations, a subset of the proposed geometrical modifications has been selected based on their economic feasibility and practical implementation. Subsequently, an in-depth exploration of the parameters associated with each of these selected geometrical alterations has been undertaken to optimize the designs. These optimized geometrical changes are then combined to determine a final, optimal design. The velocity profiles of the final optimized design are compared with those of the base model to assess the improvements achieved. Furthermore, this research extends its scope to incorporate the analysis of spatter particles generated during the metal 3D printing processes within the final-optimal geometry change. A comparative analysis between the final-optimal geometry and the base design is conducted in this context. The overarching objective of this study is to contribute valuable insights into the enhancement of inert gas utilization and spatter removal in SLM chambers, ultimately advancing the understanding and practice of this critical aspect of metal 3D printing.

1.3 Thesis Objective

The primary objective of this thesis is close the gap in the literature by implementing geometric modifications within the build chamber to improve the uniformity of inert gas flow, thereby enhancing the removal of spatter. The following steps outline the order of implementation to achieve the overarching objectives of the study:

1. **Simulation and Validation of the Chamber:** The initial step involves creating a virtual representation of the build chamber and simulating its behavior using computational methods. The simulation aims to validate the model's accuracy and ensure that it closely mirrors the real-world conditions of the chamber.
2. **Numerical Investigation of Spatter Removal Options:** Leveraging computational fluid dynamics (CFD) and numerical analysis, various options for enhancing the spatter removal process are explored. This step involves assessing how geometric changes affect inert gas flow and thereby can improve spatter removal efficiency.
3. **Comparative Evaluation of Spatter Removal Between Base Model and Final Design:** The results of the numerical investigations are comprehensively analyzed to compare the performance of the spatter removal in the base model and final design. The final design and base model are assessed in terms of its ability to improve inert gas flow and effectively remove spatter.
4. **Selection of the Optimal Solution:** Based on the evaluation of the various options, the most optimum spatter removal solution is selected. This decision is made with an emphasis on real-world implementation and the ease with which end-users can adopt the chosen solution.

The study's ultimate goal is to improve spatter removal through practical and achievable geometric changes within the build chamber.

1.4 Thesis Outline

Chapter 1 introduces the field of additive manufacturing, focusing on the specific process of Selective Laser Melting (SLM) and the challenges encountered within SLM. Additionally, it elucidates the significance and functions of inert gas flow.

In Chapter 2, an extensive literature review is conducted, encompassing topics such as spatter formation, spatter size, and the implications of spatter on the quality of parts produced through SLM. This chapter also explores the effects of scanning speed and laser power density on spatter ejection angles and velocities. Furthermore, it reviews the existing literature related to spatter angles and the techniques employed for spatter removal. Finally, it highlights the objective of the thesis.

Chapter 3 presents the numerical model and equations utilized to address issues related to gas flow and spatter within the inert gas environment. This chapter includes a grid independence study and validation of the Computational Fluid Dynamics (CFD) methods employed in this thesis. Moreover, it offers a detailed discussion of the research findings, the rationale for selecting specific geometric modifications in the final design and concludes the study.

Chapter 4 outlines potential future geometric alterations for further investigation and highlights areas for future research to enhance the current state of knowledge.

Chapter 5 concludes the study and summarizes the findings. Also, it provides references and vitae.

CHAPTER 2

LITERATURE REVIEW

2.1 Background of Additive Manufacturing

Additive Manufacturing, also known as 3D printing, is a transformative approach to industrial production that enables the creation of lighter, stronger parts and systems. The process involves creating 3D objects from a digital model by adding material layer by layer, hence the name 'additive'. This contrasts with traditional manufacturing methods which are often subtractive, removing material to create the final product. The concept originated in the 1980s, with the first patent for the stereolithography apparatus filed by Chuck Hull in 1984. However, it was not until the early 2000s that the technology garnered widespread attention due to advancements in technology and materials.

There are various techniques within additive manufacturing such as Fused Deposition Modeling (FDM), Stereolithography (SLA), Direct Metal Laser Sintering (DMLS), and Laser Powder Bed Fusion (LPBF), among others. These techniques can be used with a range of materials including plastic, metal, ceramic, and even biological material. Focusing on Laser Powder Bed Fusion (LPBF), this is a type of additive manufacturing technique that involves spreading a layer of metal powder over a build platform and selectively melting the powder with a laser beam. The platform is then lowered and the process is repeated layer by layer until the part is complete. LPBF allows for the creation of complex and highly detailed designs that would be impossible with traditional manufacturing methods. The classification of additive manufacturing can be based on several criteria:

Materials: This could include plastics, metals, ceramics, and biomaterials. In the case of LPBF, metals are commonly used.

Technology: This refers to the specific technique used, such as FDM, SLA, DMLS, or LPBF. Each technique has its own set of advantages and limitations.

Applications: This could refer to the use of additive manufacturing for prototyping, tooling, production, or personal use. LPBF, due to its ability to create complex and precise parts, is often used in industries like aerospace, automotive, and medical for the production of final parts.

Despite certain challenges such as cost and speed, additive manufacturing, and specifically techniques like LPBF, continue to revolutionize the manufacturing industry. As the technology continues to mature, its applications are expected to become even more widespread.



Figure 1. Types of additive manufacturing [19].

2.2 Laser Powder Bed Fusion

Laser Powder Bed Fusion (LPBF), also known as Selective Laser Melting (SLM) or Direct Metal Laser Sintering (DMLS), is a subcategory of additive manufacturing techniques that primarily deals with metal materials. The core principle behind LPBF involves the use of a high-power laser to fuse fine metallic powders together to form a solid, three-dimensional object. The origin of LPBF traces back to the late 1990s and early 2000s. The German Fraunhofer Institute played a significant role in its development, but several other research institutions and companies worldwide also contributed to its evolution. The technology was initially developed as a means to produce small, complex metal components for industries where precision

is paramount, such as the medical, dental, and aerospace sectors. In the LPBF process, a thin layer of metal powder is spread across a build platform, and a laser selectively traces the cross-section of the component, melting (or fusing) the metal particles together and solidifying them to form a solid mass. The build platform is then lowered, and a new layer of powder is spread on top. The process is repeated layer by layer until the part is complete. One of the main advantages of LPBF is the ability to create parts with complex geometries and internal structures, something that's often impossible or very expensive with traditional manufacturing methods. This includes intricate designs like lattice structures or internal channels. Parts produced with LPBF also tend to have good mechanical properties, comparable to those produced with conventional methods. However, LPBF also has its challenges. The process requires careful control of many parameters, such as laser power and speed, powder thickness, and temperature, to ensure a successful build. Any changes in these parameters can greatly affect the part's final properties. Despite these challenges, LPBF continues to be an important technology in additive manufacturing, driving innovations in many industries.

2.3 Spatter Formation

2.3.1 Numerical Studies

Tang et al. [1] conducted a study utilizing a 3D powder scale model to investigate the dynamics of the molten pool and the mechanisms of spatter formation during the Selective Laser Melting (SLM) process. The phase field method was employed to track the melt-gas interface, with a particular focus on analyzing how temperature variations influenced the flow over time. The research findings indicated that a spherical spatter eventually emerged from the melting pool. The authors concluded that spatter formation results from the combined effects of evaporation and the formation of a keyhole, wherein spatter is generated due to pressure recoil. The spherical shape observed in the study aligns with experimental observations in welding processes.

The mechanism underlying spatter formation is explained by the accumulation of pressure. In the keyhole, induced by evaporation, which is then expelled in the opposite direction to the scanning speed of 6.5 m/s.

A frictional interaction between the vapor and the heated pool creates a shear force at the rear of the keyhole wall. This shear force continuously acts on the back of the keyhole wall, resulting in the formation of a liquid column. Ultimately, the shear force surpasses gravity and surface tension, causing the liquid column to pinch off. Concurrently, the high-temperature melt undergoes a reduction in size due to surface tension effects. Assumptions in this simulation included the consideration of laminar flow, incompressibility of the fluid for simplicity, and the omission of heat reflection and plasma formation effects.

Wang et al. [2] also explored the mechanism of spatter formation and their findings concurred with Tang et al.'s study [1]. Their results confirmed that the formation of a keyhole is attributed to evaporation pressure at the surface, and the opposing spatter formation arises from convection effects, where lower-density material at the front travels toward lower-temperature regions at the rear, as illustrated in Figure 2.

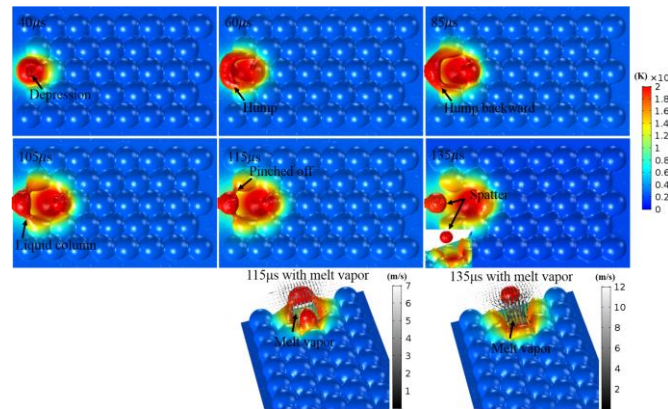


Figure 2. Spatter formation modeling [1].

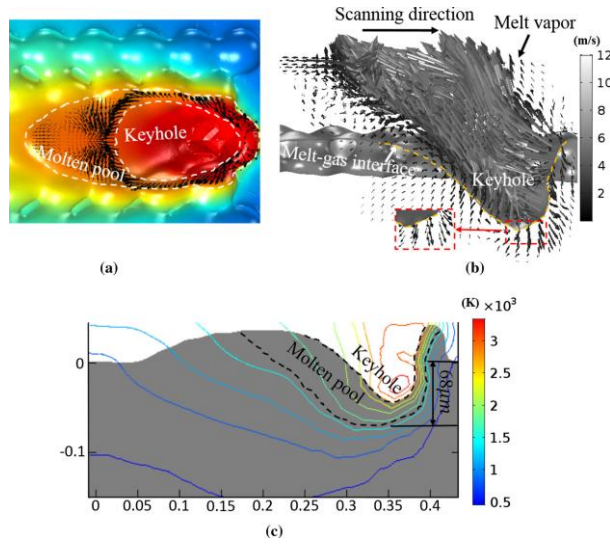


Figure 3. The keyhole is shown in a simulation of the formation of spatter [1].

Jakumeit et al. [44] conducted a study focused on analyzing complex evaporated gas flow and its influence on particle spattering during laser powder bed fusion in additive manufacturing.

The methodology employed a simulation approach using an Eulerian multiphase method, incorporating control volume discretization of the powder bed and substrate. The simulation encompassed models for metal powder heating by the laser beam and metal evaporation. Spattering particle trajectories were calculated using a Lagrangian approach for single-particle acceleration in the gas. Experimental observations using synchrotron X-ray imaging were also compared with simulation results.

Results indicated that particle acceleration varied with line energy, increasing linearly in the conduction mode, decreasing linearly in the transition mode, and then increasing again in the keyhole mode. The study further analyzed the impact of process parameters, such as laser power and speed, on the maximal acceleration of particles from the melt pool area.

The study's conclusion emphasized that the combination of the Eulerian multiphase approach and Lagrangian calculation effectively described individual particle acceleration in the gas stream. Additionally, the study proposed a novel volume averaging methodology to calculate maximal particle acceleration based

on the Eulerian model without computationally expensive Lagrangian calculations. Overall, the study underscored the importance of comprehending gas flow dynamics and its implications for particle spattering to enhance the quality of additive manufacturing components.

Khairallah et al. [47] conducted a comprehensive study on the physics and mechanisms underlying the formation of pores, spatter, and denudation zones in laser powder-bed fusion additive manufacturing. The research focuses on understanding the impact of recoil pressure and Marangoni convection on shaping the melt pool and their contribution to the emergence of pore defects, material spattering, and denudation zones.

The study utilizes a three-dimensional high-fidelity powder-scale model, incorporating laser ray-tracing energy deposition, an improvement over traditional volumetric energy deposition methods. The ALE3D massively-parallel multi-physics code is employed, and the results are validated against experiments with discussions on laser absorptivity sensitivity.

Key findings include the subdivision of the melt track into three differentiable regions: a depression region at the laser spot, a tail end region near the end, and a transition region in between. The depression region, marked by the highest temperatures, is identified as the site of spattering and denudation. Recoil flow pressure and Marangoni convection are highlighted as crucial factors shaping the melt pool and contributing to pore and spatter formation.

The study delves into the effects of dynamic melt flow, including depression formation and liquid build-up spilling over onto powder particles, resulting in spatter particles in the powder bed. Lateral shallow pores and trapped incompletely melted particles in the transition flow region are also explored.

In conclusion, the study underscores the importance of understanding the intricate physics processes involved in laser powder-bed fusion additive manufacturing, emphasizing their strong dependence on temperature. Recommendations include avoiding deep and narrow depressions to reduce pore formation, adjusting laser intensity during direction changes along a scan track, employing appropriate scan vector

overlap, and implementing a gentle ramping down of laser power to prevent end-of-track pores and side surface roughness. Overall, the study provides valuable insights into mitigating pore formation and improving the quality of manufactured parts in laser powder-bed fusion additive manufacturing.

2.3.2 Experimental Studies

Andani et al. [22] also, conducted a study on the impact of energy input on the generation of spatter particles during the selective laser melting (SLM) process. The research explored the formation mechanisms and dynamic behavior of spatter particles, evaluating their distribution under varying energy inputs. Additionally, the study examined the correlation between the number of spatter particles, induced unmelted regions, and density variability in SLM parts, with the aim of providing insights for optimizing manufacturing process parameters in SLM. The methodology of the study involved the use of high-speed photography to capture the formation mechanisms and dynamic behavior of spatter particles during the selective laser melting process. An image processing analysis framework was then applied to assess the distribution of spatter particles under different energy inputs. Microscopic examination and density analysis of SLM parts were also conducted using an SLM machine equipped with two 400 W CW Ytterbium fiber lasers and pre-alloyed Al-Si10-Mg powder for printing. The density of the samples was calculated using the Archimedes principle, and a high-speed camera was employed to observe spatter formation. The study revealed that the number and size of spatter particles during the selective laser melting process were influenced by the energy input. Specifically, increasing laser power and decreasing laser scan velocity resulted in higher energy input and recoil pressure, leading to the creation of a greater number of spatter particles. Furthermore, the research highlighted that the effects of laser scan velocity on spatter particle production were more pronounced than those of laser power. It was also found that the presence of unmelted regions caused by spatter particles could lead to a loss of density in the final printed parts. In conclusion, the study emphasized that optimizing manufacturing process parameters by minimizing laser energy input to reduce spatter particles alone is insufficient to enhance the mechanical properties of final

SLM products. It stressed the importance of fabricating parts with minimal spatter particle creation during the manufacturing process and minimizing the presence of un-melted regions in the final SLM products. The study underscored the need for further research to develop optimization methods for minimizing un-melted regions induced by spatter particles and to investigate SLM specimen defects using 3D techniques.

Ye et al. [26] conducted a study focusing on investigating the plume and spatter signatures during selective laser melting (SLM) and examining their relationship with the melted states. The research delves into the distinctive plume and spatter signatures associated with different melting processes, exploring how they vary with changes in laser power and scanning speed. The study underscores the role of laser power in the melting process, particularly in comparison to scanning speed. The methodology employed comprises both experimental analysis and simulation to analyze the stability of the SLM process by studying plume and spatter signatures separately. The generation of droplet and particle spatter is elucidated through a combination of experimental results and simulations, with a specific focus on understanding its relationship with melt-pool behavior. The study utilizes a logistic regression model to estimate different states corresponding to laser energy density. Spatter particle distribution is assessed under various energy inputs, and a thermal camera is utilized to analyze spatter signatures, obtaining size and shape data of the melting pool. The study achieves different relative densities of workpieces by altering the scanning strategy and also investigates plume characteristics of the metal powder during the SLM process. Results from the study indicate that variations in laser scanning speed have a greater influence on spatter formation compared to laser power. Parameters such as spatter size, jetting height, scattering state, and number impact the morphology and quality of the melted states. The study further reveals that plasma temperature decreases with an increase in the Q-switching rate, and temporal temperature changes occur at a slower speed than the electron density in the plume. Images and data obtained from the study showcase melted track widths and features at different scanning speeds and laser powers, identifying distinct melted states such as normal states, underheating states, and overheating states. The study emphasizes the importance of monitoring plume and spatter signatures to avoid defects during the selective laser melting process. The melted states

are found to be influenced by the laser energy density, determined by laser power and scanning speed. Understanding and controlling plume and spatter signatures are identified as crucial factors for achieving desired melted states and preventing defects in the selective laser melting process.

Wang et al. [32] conducted a study investigating the mechanisms and characteristics of spatter generation in selective laser melting (SLM) processing and its consequential effects on the properties of fabricated parts. The study aimed to understand the intensity and quantity of spattering as the laser energy input increased. Three main sources of spattering were identified: recoil pressure, the Marangoni effect, and heat effects in the molten pool. The research also explored the composition and size of spattering particles and their impact on both the surface and interior of SLM-fabricated parts. Experimental methods were employed to investigate spattering in SLM processing, utilizing a high-speed camera to record dynamic spattering of CoCr alloy during the SLM fabrication process. The laser power was adjusted to vary energy input, and the resulting impact on spattering was observed. Spattering particles were collected and analyzed using a grain size analyzer, scanning electron microscope (SEM), and energy-dispersive X-ray spectroscopy (EDS). Carbon and oxygen content in both the original powders and spattering particles were examined using an organic chemical element analyzer, and X-ray diffraction analysis was conducted to examine the phase constitution of the powders. The study's results revealed that the intensity and quantity of spattering increased with higher laser energy input in SLM processing. Different types of spattering were identified, each with distinct morphologies (type-I, type-II, and type-III). Spattering particles exhibited larger sizes and varied shapes compared to the initial powders, with some particles displaying spherical or near-spherical morphology. The analysis also indicated an increase in carbon and oxygen content in spattering particles compared to the original powders. Furthermore, the presence of spattering particles was found to introduce impurities and holes in fabricated parts, impacting surface quality and mechanical properties.

In conclusion, the study highlighted that the intensity of spattering in SLM processing is influenced by laser energy input, with increasing intensity and quantity as energy input rises. The identification of different

spattering types and the understanding of their morphology provide valuable insights for controlling spattering intensity, ultimately contributing to the improvement of stability and repeatability in the SLM fabrication process.

Gunenthiram et al. [33] conducted a study focusing on the experimental analysis of spatter generation and melt-pool behavior during the powder bed laser beam melting process. The primary objectives were to quantify and comprehend the formation of spatters in selective laser melting (SLM) and explore the potential influence of melt-pool behavior and key-hole formation on these instabilities. The study utilized an instrumented SLM setup to analyze spatter ejections and their correlation with melt-pool behavior, with a specific examination of the effect of volume energy density (VED) on spatter formation and a comparison of different materials, such as 316L stainless steel and Al-12Si alloys. In the experimental approach, single SLM beads were conducted on an instrumented SLM setup, employing incremental SLM conditions with laser powers ranging from 100 W to 1500 W and scan velocities up to 0.75 m/s. A high-speed camera captured and analyzed melt-pool and spatter formation at different collection angles, and image analysis software was employed to analyze spatters in terms of numbers, size, and surface ratio. The process conditions were chosen to provide a similar range of VED and bead penetration as commonly used in SLM machines, and statistical analysis was performed to ensure reliable data. The study's results revealed that spatter generation increases with VED, except for conditions that provoke balling. A clear distinction in spatter amount between aluminum and steel materials was observed. The occurrence of humping instabilities did not show a clear correlation with spatter ejection. Spatters were formed in the powder bed near the melt-pool, attracted to the melt-pool surface by Bernoulli-like effects, and ejected upwards. Large spatters (>0.1 mm) were confirmed to contaminate powder bed surfaces and generate inclusions in solidified parts. The influence of laser power on spatter generation was not evident for aluminum alloys. The study suggested that suppressing spatters is achievable by considering low VED values combined with larger spot diameters. Additionally, adopting a near-1D conduction regime with sufficient molten depth and direct incorporation of droplets into the melt-pool can preserve the powder bed surface and enhance the

quality of SLM parts. In conclusion, the study emphasized that spatter formation during the powder bed laser beam melting process can be influenced by factors such as VED, laser power, and material properties. The findings confirmed the occurrence of large spatters with potential impacts on powder bed surfaces and solidified parts. The study proposed adjustments to process parameters to suppress spatters and highlighted the significance of considering melt-pool behavior and key-hole formation in understanding spatter generation and melt-pool dynamics. Overall, the study contributes valuable insights for optimizing the powder bed laser beam melting process to minimize spatter generation and enhance the quality of fabricated parts.

Özel et al. [38] study focused on advancing the process control capability of laser powder bed fusion (LPBF) through the in-situ monitoring of spatter and overmelting regions using high-speed camera videos. The research employed statistical methods, including principal component analysis (PCA), to analyze temporal-spatial characteristics.

Using real-time high-speed camera videos, the study conducted temporal PCA to monitor meltpool areas and spatial vectorized PCA to track spatter locations. Statistical analyses, including mean and standard deviation calculations, were applied to assess process control capabilities. The study provided valuable insights into the temporal and spatial aspects of the LPBF process, enabling the identification of different meltpool types and mapping primary and secondary spatter spikes.

In conclusion, the combination of temporal and spatial analysis, supported by high-speed camera videos and statistical tools, demonstrated effective process monitoring and control for LPBF. The study proposed the use of stochastic models derived from statistical analysis for predicting spatter occurrence and size, contributing to long-term production consistency and emphasizing the significance of process monitoring in identifying potential process changes.

Eschner et al [41] conducted a study on the correlation between spatter behavior and process zone formation in powder bed fusion of metals using high-speed stereoscopic imaging. The methodology employed high-

speed stereoscopic imaging to measure three-dimensional (3D) time-resolved spatter trajectories, and statistical measures of these trajectories were correlated with the transition from heat conduction mode to evaporation-dominated mode in the interaction zone and its geometry. The study's results indicate a correlation between the evolution of spatter speed and the transition from heat conduction to an evaporation-dominated process regime. Additionally, the measured penetration depth of the weld tracks was found to be related to the in-situ measured penetration depth based on the median spatter ejection angle. The study concludes that the spatter signature is a valuable measure during powder bed fusion of metals, enabling the observation of microscopic process features from a macroscopic perspective. The results suggest that the spatter signature can be used to identify process errors and detect shifts in the process regime.

Shuai et al [43] conducted a study focusing on the effect of spattering on the formation mechanisms of metal matrix composites (MMCs) in laser powder bed fusion (LPBF), with diamond grinding wheels (GWs) as a specific example.

The methodology involved fabricating bronze-bond GWs with diamond grains using LPBF, analyzing surface morphology, porosity ratio, pore morphology, and flexural strength of the GWs with different processing parameters. The study also included a theoretical analysis of the diamond spattering generation mechanism and electrical discharge grinding (EDG) of a reaction-bonded silicon carbide workpiece using the fabricated GWs.

Results encompassed the characterization of surface morphology, porosity ratio, pore morphology, and flexural strength of the diamond GWs under different processing parameters. The study also analyzed the grinding performance of the GWs compared to a bronze alloy grinding tool in terms of surface roughness and morphology of the workpiece.

The conclusion highlighted the significant impact of spattering on the formation mechanisms of metal matrix composites in LPBF. The study provided insights into the evolution of surface morphology, porosity

ratio, pore morphology, flexural strength, and grinding performance of diamond GWs. It emphasized the importance of considering spattering in both the fabrication and application of metal matrix composites.

Zhang et al [46] performed investigation delves into understanding the influence of part geometry on spatter formation in the laser powder bed fusion of Inconel 718 alloy, utilizing optical tomography. The study aims to develop experimental strategies for tracking powder history and evaluating the degradation of reused powder.

The methodology involves employing the Laser Powder Bed Fusion (L-PBF) process with Inconel 718 alloy powder and default processing parameters using an EOS M290 machine. The build chamber is filled with argon gas during the process. Optical tomography (OT) is used as an on-line monitoring tool to capture thermal radiation from the build area. The OT images are analyzed using MATLAB software to extract grayscale values (GVs) from each pixel, allowing for the evaluation of melt pool intensities and emissions from spatter particles.

Powder-capturing containers with internal lattice structures of varied beam lengths and diameters are used to examine the effects of part geometry on spatter emissions. The collected powder samples undergo further analysis, including surface morphology, microstructure, and surface chemical state using high-resolution scanning electron microscopy (HR-SEM) and X-ray photoelectron spectroscopy (XPS). Bulk oxygen content is measured using combustion analysis, and particle size distribution measurements are performed.

Results from the study indicate that part geometry significantly influences spatter formation in the laser powder bed fusion of Inconel 718 alloy. Spatter particles with longer trajectories exhibit lower grayscale values (GVs), indicating a rapid temperature drop as they depart from the melt pool. Components with higher surface-to-volume ratios and larger areas of overhangs generate more spatter, leading to increased oxygen content in the collected powder samples. The study establishes correlations between the area fraction of the laser-irradiated region and the occurrence of spatter trajectories, emphasizing the crucial role of part geometry in spatter formation during laser powder bed fusion.

Criales et al. [48] conducted a study focusing on the effects of process parameters and scan strategy on melt pool size and shape in the laser powder bed fusion of nickel alloy 625. The primary objectives were to determine the relative density, dimensions, and shape of the melt pools in fabricated test coupons, gaining a comprehensive understanding of the laser fusion processing of powder material. The study also delves into the analysis of in-situ thermal camera video recordings to examine melt pool size, spattering particles, and heating and cooling rates during the process.

The methodology involves a combination of experimental design, response surface methodology (RSM), and various measurement techniques. Test coupons are fabricated with different process parameters selected from the RSM design, and melt pool size and shape are measured using digital optical microscopy (DOM) and thermal camera imaging. In-situ thermal monitoring and video recordings are utilized to analyze the melt pool size and investigate spattering phenomena. The study includes post-processing operations to align temperature histories and construct average temperature profiles.

The results contribute valuable process information for further validation of modeling studies and adoption in industrial practice. The dynamic nature of the melt pool is identified, constantly changing as the laser scans and moves along a single track, highlighting a dynamic melt pool phenomenon. The study reveals that melt pool size slightly increases with higher energy density, particularly affecting melt pool depth more than width. Melt pool shape is found to be non-linear, influenced by factors such as hatch distance, laser power, and scan velocity. Different types of melt pools obtained under the same conditions exhibit considerable shape variations, with Type I melt pools being more asymmetric. The study also provides insights into the effects of low hatch distance and high laser power on melt pool shape.

The main conclusion emphasizes the identification and definition of a dynamic melt pool in laser powder bed fusion of nickel alloy 625. This dynamic nature underscores the importance of considering varying melt pool sizes in future research for microstructure characterization and calculating mechanical properties of additively manufactured parts. The study underscores the need for continued research and understanding

of the effects of process parameters on melt pool size and shape to enhance the quality and structural integrity of additively manufactured parts in nickel alloys.

Liu et al. [49] conducted a study focused on examining the correlation between gas flow parameters and droplet spatter features and dynamics during large-scale laser powder bed fusion.

The methodology employed in the study included capturing spatter in large-scale laser powder bed fusion using a high-speed camera. Image processing techniques were applied to extract spatter information, encompassing spatter areas, ejecting velocity, and spatter count. Statistical analysis was performed to investigate droplet spatter features and dynamics under varying gas speeds and scanning directions.

The results revealed a strong correlation between droplet spatter features and dynamics and gas flow velocity. As gas velocity increased, the spattering angle decreased, the quantity of micro-spatter increased, and the maximum spattering speed of the droplets rose. The study identified that a gas velocity of 1.5 m/s minimized spattering behavior. Interestingly, the spatter number and total spatter area initially decreased and then increased with higher gas flow velocity. These findings provide valuable insights into the relationship between gas flow parameters and droplet spatter behavior in the context of large-scale laser powder bed fusion.

In conclusion, the study emphasizes that gas flow parameters, specifically gas flow velocity, significantly influence droplet spatter features and dynamics during large-scale laser powder bed fusion. Higher gas velocities were associated with smaller spattering angles, increased micro-spatter generation, and higher maximum spattering speeds. The identification of an optimal gas velocity of 1.5 m/s highlights the importance of fine-tuning gas flow parameters to control and minimize spatter formation during the laser powder bed fusion process.

Sutton et al. [50] conducted a study focusing on the characterization of laser spatter and condensate generated during the selective laser melting (SLM) process of 304L stainless steel powder. The study aimed

to examine the morphological, chemical, and microstructural differences between virgin powder and heat-affected powder formed during the SLM process, providing valuable insights into laser spatter and condensate.

The methodology employed various characterization techniques, including particle size and shape distribution measurements, energy-dispersive spectroscopy (EDS), Raman spectroscopy, inert gas fusion, metallography, and x-ray diffraction. SEM imaging and analysis, including automated feature analysis (AFA) for particle size distributions, were also utilized.

The results of the study revealed that the ejected laser spatter from the melt pool exhibited coarser particles compared to virgin 304L powder, as indicated by larger particle size values. Laser spatter particles were found to contain a higher amount of oxygen compared to virgin powder, attributed to their slower cooling rate within the build chamber atmosphere. The study also observed the presence of oxides on the surface of laser spatter particles. However, bulk chemistry analysis showed no significant differences in elemental concentrations between virgin and heat-affected powders.

The study concluded that laser spatter and condensate are formed under different circumstances during the selective laser melting process. Laser spatter comprised coarser particles, while condensate exhibited submicron size. The presence of condensate on the surfaces of laser spatter particles suggested that a portion of condensate deposits in the build area along with the spatter. The study also highlighted the potential influence of condensate on part properties, indicating that the presence of nanoparticles on the surfaces of laser spatter could alter adhesion and friction properties of powders. Overall, the results provided valuable insights into the mechanisms responsible for powder property evolution and contributed to a better understanding of the recyclability of powder in selective laser melting processes.

2.4 Spatters Distribution and Features

Furumoto et al. [4] conducted a series of experiments to investigate the behavior of spatter formation during the additive manufacturing process. They employed two high-speed cameras operating at 5000 frames per second (f/s) to capture Scanning Electron Microscopy (SEM) images of the process. One camera was positioned at a 0° angle, while the other was set at a 45° angle. The experiments involved the use of maraging steel powder with a median diameter of $24\text{ }\mu\text{m}$, with 10% of the powder particles having a diameter of $41\text{ }\mu\text{m}$. The layer thickness was maintained at $50\text{ }\mu\text{m}$, and a laser power of 300W was utilized. A total of 100 images were collected and analyzed to evaluate spatter behavior.

The study focused on assessing various parameters, including spatter counts, ejection angles, and the distribution of spatter sizes. Furumoto et al. [4] utilized four substrates with different surface roughness values (0.13 , 0.79 , 1.78 , and $3.34\text{ }\mu\text{m}$) to examine their influence on spatter behavior. The findings revealed that for substrates with a surface roughness of $3.34\text{ }\mu\text{m}$, the majority of spatter was ejected in front of the melting pool at the boundary of the denuded area and was subsequently disposed of as metal powder. In contrast, for substrates with a surface roughness of $0.13\text{ }\mu\text{m}$, most of the spatter was ejected closer to the melting pool, with 11% originating from the melting pool itself. The relationship between surface roughness and spatter behavior was explored revealing that higher surface roughness correlated with reduction in the number of spatter particles with increased ejection angles and velocities. Lastly, the shape of the spatter particles was consistently spherical, and their composition closely resembled that of the virgin powder. These findings provide valuable insights into the behavior of spatter in additive manufacturing processes, particularly in relation to surface roughness and ejection characteristics.

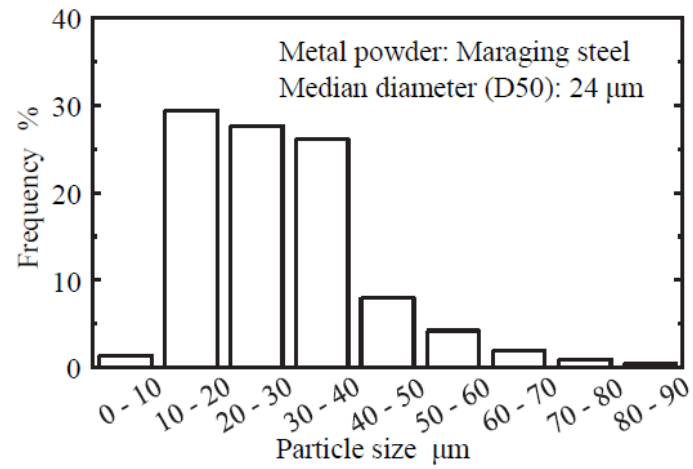


Figure 4. Virgin powder size distribution [4].

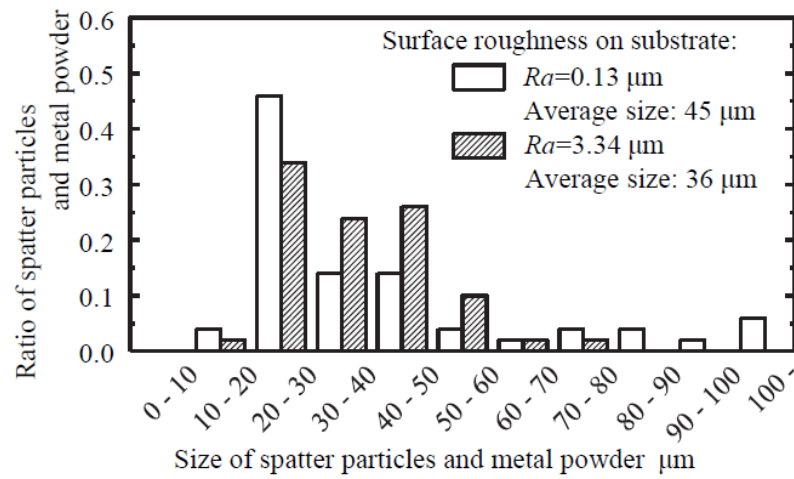


Figure 5. Comparison between two different surface roughness for spatter and metal powder size ratio [4].

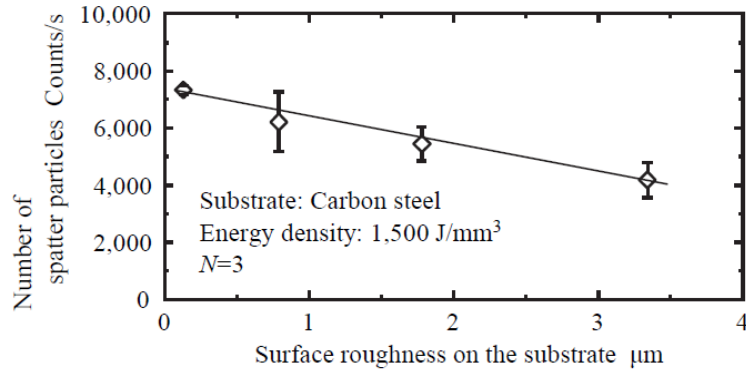


Figure 6. Correlation of the spatter particle counts with the surface roughness on the base plate [4].

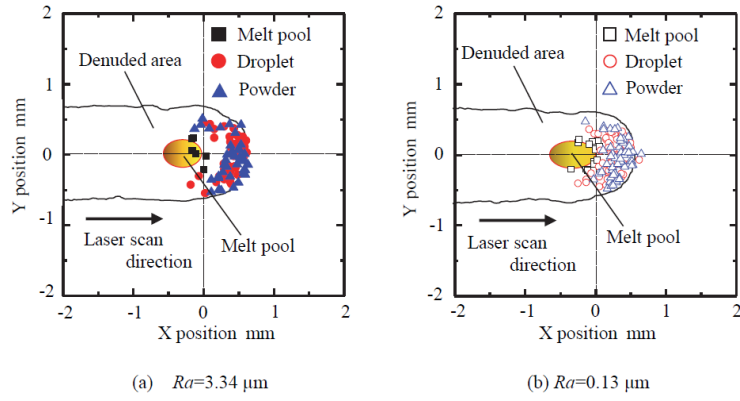


Figure 7. Spatter production initial location [4].

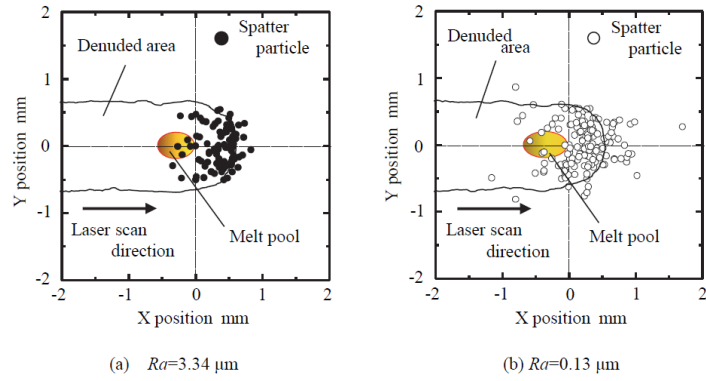


Figure 8. Ejection direction from initially produced location [4].

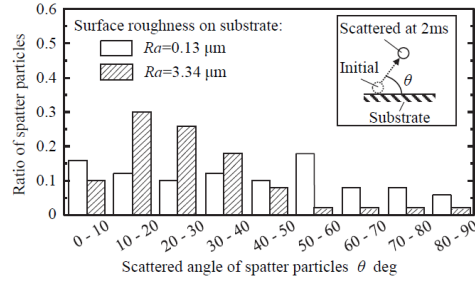


Figure 9. Angle distribution for the two-surface roughness [4].

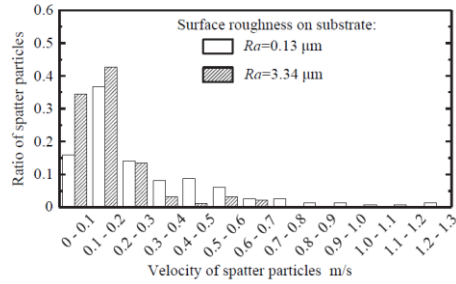


Figure 10. Velocity distribution of both surface roughness [4].

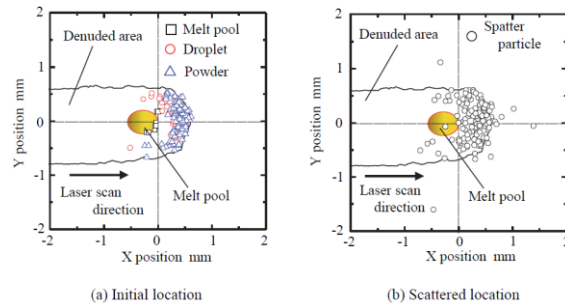


Figure 11. Spatter particle movement on the substrate [4].

Anwar & Pham, [27] conducted a study focusing on the distribution of spatter particles on the powder bed during the selective laser melting process in additive manufacturing. The primary objective was to quantify the spatter distribution on the powder bed and analyze the impact of gas flow velocity on spatter deposition. Additionally, the study aimed to investigate the correlation between spatter mass and the percentage of spatter pixels detected through image processing. The study employed image acquisition, processing, and analysis techniques to characterize the spatter distribution on the powder bed. Top-down images of the

powder bed were captured using a camera and processed using image processing software. The Renyi entropy thresholding method was applied to segment the images into spatter and background regions, enabling the determination of the percentage of spatter pixels per column, representing the spatter distribution. Spatter particles were also collected and sieved for size analysis using optical microscopy, and SEM analysis was conducted on collected spatter samples for high magnification images and elemental testing. The key results of the study revealed a positive linear relationship between the percentage of spatter pixels and the mass of spatter, indicating the effectiveness of the image processing methodology in quantifying spatter distribution. The largest spatter particles, both in terms of mass and size, were observed to be deposited closest to the scanned regions, gradually decreasing in the downstream direction of the gas flow. The study further identified three types of spatter: metallic jet spatter, droplet spatter, and unmelted powder spatter. An increase in gas velocity was found to transport heavier and larger spatter particles, resulting in a more even distribution downstream of the gas flow. In conclusion, the study highlighted that the image processing methodology employed was an effective tool for quantifying spatter distribution during selective laser melting. The positive linear relationship between the percentage of spatter pixels and spatter mass demonstrated the reliability of the method. The observed deposition patterns of spatter particles and the influence of gas velocity provided valuable insights. The study recommended further tests to enhance the credibility and suitability of the proposed method as a simple and efficient in-situ spatter characterization technique in selective laser melting.

2.5 Effect on the Quality

Guo et al. [23] conducted a study on the transient dynamics of powder spattering in the laser powder bed fusion additive manufacturing process. The research utilized in-situ high-speed high-energy x-ray imaging to gain insights into the intricate details of the process, overcoming limitations posed by conventional characterization tools. The study employed a high-speed high-resolution high-energy x-ray imaging technique, capable of capturing details at a spatial resolution of up to 1 μm with a tunable frame rate of up

to 1 MHz. A focused laser beam was applied from the top of the powder bed, with laser parameters controlled using a galvanometer scanning system. The experiments were conducted in a vacuum chamber refilled with argon gas. Key findings of the study include the significant influence of environmental pressure on powder spattering behavior. Higher environmental pressure led to a decrease in the amount of powder spatter. Insights into the transient dynamics of powder spattering were provided, encompassing the initiation process and mechanisms of powder motion during the laser powder bed fusion process. The process involved localized laser melting, followed by the generation of an intensive vapor jet and the flow of argon gas. Each step was estimated to occur within microseconds for melting, tens of microseconds for vapor jet/plume formation, and hundreds of microseconds for argon gas flow formation. The study's major conclusions are summarized as follows: In the laser powder bed fusion process, localized laser melting occurs, followed by the generation of an intensive vapor jet and argon gas flow. The time for each step is estimated to be in the order of microseconds, tens of microseconds, and hundreds of microseconds, respectively. Environmental pressure plays a crucial role in controlling powder spattering behavior. Higher pressure results in a decrease in total spatter amount, while the amount of hot spatter increases. Tuning environmental pressure can balance the amount of hot spatter and total spatter, thereby improving part quality. The study provides insights into the transient dynamics of powder spattering, including the initiation process and mechanisms of powder motion. It reveals the influence of environmental pressure on divergence angle, spatter amount, and spatter speed. Overall, the study enhances our understanding of the powder spattering phenomenon in the laser powder bed fusion additive manufacturing process, offering valuable information for optimizing process parameters and improving part quality.

Wang et al. [24] conducted a study on the influence of spatter particles contamination on the densification behavior and tensile properties of CoCrW alloy fabricated through selective laser melting (SLM). The study utilized a selective laser melting (SLM) machine to manufacture CoCrW alloy components and investigated the impact of powder reusing time on the fabrication process. High-speed imaging was employed to observe the spattering process and the resulting powder pollution caused by spatter particles. The study analyzed

the densification mechanism and the evolution of the microstructure of the printed components. Mechanical properties of the components printed using powders contaminated by spatter were tested at different stages of the life cycle, adhering to ISO standards for specimen preparation, process parameters, and test conditions. Tensile strength tests were conducted using an electronic universal testing machine, and surface morphology and fracture analysis were carried out using a scanning electron microscope. The study observed that spatter particles generated during the selective laser melting (SLM) process were more complex and larger in size compared to virgin powder particles, exhibiting irregular shapes and a tendency to adhere together. The presence of spatter in the powder significantly impacted the mechanical properties of the SLM-ed parts. Specifically, parts fabricated with virgin powder demonstrated higher tensile strength, yield strength, and elongation compared to parts fabricated with powders that had been reused multiple times. The performance of the parts degraded as the powder usage time increased. Additionally, the study found that the residual pore size increased with the number of powder usage times, and un-melted powder appeared in long and narrow pores. Conclusively, the study highlighted that the contamination of metallic powder by spatter particles during the selective laser melting (SLM) fabrication of CoCrW alloy has a substantial negative influence on the densification and mechanical properties of the fabricated parts. The presence of spatter in the powder resulted in the formation of larger residual pores and the appearance of un-melted powder in the microstructure. As the powder usage time increased, the performance of the fabricated parts, including tensile strength and yield strength, decreased. The study emphasized the necessity for further investigation into the influence of spatter on the microstructures and performance of manufactured parts.

Gaspar et al. [25] conducted a comprehensive study investigating spatter metallurgy in the laser powder bed fusion (PBF-LB) of Inconel 718, with a particular emphasis on discerning differences in spatter particles and their surface oxide formations. The study employed a combination of analytical techniques to provide a detailed understanding of the spatter characteristics. Scanning electron microscopy (SEM) and back-scattered electron imaging were used to capture compositional and morphological differences in the

powder particles. In situ focused ion beam (FIB) milling and cross-sectional analysis of particles were performed using a dual-beam FIB/SEM system. Energy-dispersive X-ray spectroscopy (EDS) was employed to characterize and map powder composition, while laser diffraction analyzed the particle size distribution. For nanoscale characterization, vaporized material was collected on Cu TEM grids and scrutinized using a transmission electron microscope (TEM) equipped with TEM-EDS. The study's key findings revealed that spatter particles generated during the laser powder bed fusion (PBF-LB) of Inconel 718 differed significantly from the virgin material in terms of size, shape, morphology, and the presence of oxides. Various types of spatter particles were identified, encompassing those similar to virgin gas atomized particles, particles with altered morphology, larger singular particles, particles with oxide spots, particles covered with oxide, small particles, and agglomerates. Oxide formation was observed on a proportion of spatter particles, with some particles completely oxidized. The size distribution of spatter particles was larger than the starting powder, and the presence of oxides on these particles had the potential to impact the quality and properties of the consolidated material. The study underscored the significance of comprehending the generation and effects of spatter particles within the powder bed during PBF-LB processing. Notably, the study concluded that spatter generated during laser powder bed fusion processing can redeposit into the powder bed, even in areas where parts are yet to be scanned. Consequently, each processed powder layer at any given time is a combination of virgin powder and spatter. The presence of spatter particles, especially those with oxide formations, carries the potential to introduce defects in the build. Therefore, understanding the generation and potential effects of these particles is crucial for enhancing the quality and properties of the consolidated material. The study called for further investigation, particularly regarding powder recycling and the impact of spatter on the processing of Inconel 718 and other alloys.

Repossini et al. [29] conducted a study examining the viability of utilizing spatter-related information to characterize the quality of the Laser Powder Bed Fusion (LPBF) process in metal additive manufacturing. The research explores the application of high-speed image acquisition, image segmentation, and feature

extraction to estimate statistical descriptors of spattering behavior along the laser scan path. Additionally, the study develops a logistic regression model to assess the ability of spatter-related descriptors to classify different energy density conditions corresponding to various quality states. The methodology employed high-speed machine vision to capture in-situ image streams along the scan path of the laser in the LPBF process. Image segmentation and feature extraction techniques were then applied to estimate statistical descriptors of spattering behavior, including spatter area, number, and spatial spread. The study introduced a novel method for determining the spatial spread of spatters as the laser beam moved along the scan path. A logistic regression classification model was developed to evaluate the relevance of spatter-related descriptors in classifying different melting conditions. Results demonstrated that incorporating spatter-related information as a process signature driver significantly enhanced the capability to detect under-melting and over-melting conditions in the LPBF process. Spatter behavior, characterized by statistical descriptors such as spatter area, number, and spatial spread, provided additional information for classifying different melting conditions compared to analyzing the laser heated zone alone. The logistic regression classification model, incorporating spatter-related descriptors, exhibited improved performance in classifying under- and over-melting conditions. The study emphasized the importance of considering data acquired along the border scan for accurate melting state classification. The text further discussed the significance of in-situ sensing and process monitoring techniques in overcoming technological barriers in metal additive manufacturing systems, particularly at the track level, to quickly detect defects during production. The study concludes by suggesting that spatters can be used as additional process signatures in LPBF process monitoring, potentially in combination with other sensing techniques. Future research efforts are proposed to focus on incorporating spatter signatures into statistical process monitoring tools and investigating their suitability for detecting transitory events and localized defects.

Esmailizadeh et al. [30] conducted a study investigating the influence of spatter particles distribution on the quality of Hastelloy X parts produced through laser powder-bed fusion additive manufacturing. The research comprehensively examined the chemical composition, phases, microstructure, morphology,

thermal behavior of both virgin and spatter powders, and further analyzed the surface roughness of the printed parts. The impact of spatter particles on part density and internal properties was also investigated.

The study utilized laser powder-bed fusion additive manufacturing to produce Hastelloy X parts, employing specific processing parameters such as laser power, laser velocity, layer thickness, and hatching spacing. The build plate temperature was maintained at a specified level during the manufacturing process. Post-manufacturing, spatter powders were collected from around the build plate and above the argon blowers. Various characterization methods, including scanning electron microscopy (SEM), X-ray diffraction (XRD), differential scanning calorimetry (DSC), helium pycnometry for density measurement, and confocal laser microscope for surface roughness measurement, were employed. Computed tomography (CT) was also utilized to analyze the density and porosity of the printed parts. The study revealed significant findings. The distribution of spatter particles across the build plate had a substantial impact on the surface roughness of the printed parts. Regions rich in spatter particles exhibited higher roughness on all surfaces compared to regions in the middle of the build plate. Spatter particles introduced irregularities in the powder layer, hindering complete melting and increasing the likelihood of lack of fusion and pore formation. Parts printed in spatter-rich regions showed more porosity and elongated pores with irregular shapes compared to parts from low spatter regions. The chemical composition of the spatter particles closely resembled that of the virgin powders, indicating that major alloying elements were not significantly affected by spatter formation. The thermal behavior and melting range of virgin and spatter powders were similar, suggesting that the introduction of spatter powders did not alter the overall thermal behavior of the build plate. The density of the printed parts was inversely proportional to the layer thickness, and the presence of spatter particles increased the overall layer thickness, potentially affecting part density. In conclusion, the study underscores the importance of considering the distribution of spatter particles in laser powder-bed fusion additive manufacturing processes, as it significantly impacts surface quality, density, and internal properties of the printed parts.

Gaspar et al. [31] conducted a study focusing on the formation of oxide and spatter powder during the laser powder bed fusion process of Hastelloy X and its subsequent impact on the integrity and recyclability of built parts. The study employed laser powder bed fusion (PBF-LB) experiments using Hastelloy X powder with specific parameters such as laser power, scan speed, hatch distance, substrate temperature, and layer thickness. Spatter powder samples collected from the build chamber underwent analysis using backscattered-electron scanning electron microscopy (BSE-SEM), energy dispersive X-ray spectroscopy (EDS), and image analysis software. The surface chemistry of the powders was further analyzed using X-ray photoelectron spectroscopy (XPS). The results of the study highlighted key findings. Spatter particles produced during the laser powder bed fusion process exhibited differences from virgin powder particles in terms of size, shape, morphology, and the presence of oxides. The spatter particles demonstrated increased agglomerates and irregularities compared to the virgin powder, with approximately 7.4% of the spatter particles found to be oxidized. Analysis also identified various types of oxides, such as Cr and Si oxides, on cube surfaces and single tracks. The study suggested that oxidation initiated at the melt pool level, potentially serving as nucleation sites for larger oxides to develop over multiple layers. The presence of elements with high oxidation potential, even in small concentrations, played a significant role in oxide formation. The study concluded that oxide formation occurs in Hastelloy X during the laser powder bed fusion process, despite processing in an atmosphere with low oxygen concentration. Oxide inclusions were observed in the built parts, posing potential implications for their integrity and recyclability. The presence of spatter particles, containing oxides, was identified as a contributing factor to defects such as porosity, lack of fusion, and inclusion defects in the built parts. Consequently, the study underscored the importance of maintaining tight tolerance and control in powder specifications and quality to minimize the incorporation of oxidized spatter particles into parts. Additionally, it emphasized the necessity of understanding the mechanisms of oxide formation in spatter and the conditions leading to the development of different oxide structures.

Snow et al. [34] conducted a comprehensive study on spatter-induced lack-of-fusion in laser-based powder bed fusion (L-PBF) components. The research focused on establishing spatial and morphological relationships between spatter particles and internal flaws, investigating causal links, and exploring the impact of inert gas flow and laser trajectory. The study employed an L-PBF build with various test geometries, including spatter generators, XCT coupons, and in situ sensors. Powder samples were characterized using scanning electron microscopy, and flaws were identified through XCT reconstructions and deep learning algorithms. Spatial correlations between spatter and flaws were quantified, and mitigation strategies were explored.

The study's key findings include the identification of a spatial correlation between spatter particles and internal flaws in L-PBF components. In situ monitoring and XCT data revealed a direct relationship between detected spatter particles and internal porosity. The study employed a well-trained spatter detection network, achieving accurate segmentation with a low false-positive rate. Statistical analyses using the CLQ method confirmed a significant correlation between the presence of spatter particles and flaws.

Moreover, the study investigated the influence of inert gas flow and laser trajectory on spatter occurrence and distribution. Peaks in spatter particle amounts were linked to specific layer numbers and laser trajectory angles, emphasizing the role of process parameters in spatter-induced defects.

In conclusion, the study establishes spatter-induced lack-of-fusion as a significant mechanism for generating stochastic flaws in L-PBF components. The spatial correlation between spatter particles and internal flaws underscores the direct responsibility of spatter in creating lack-of-fusion defects. Mitigation strategies, such as optimizing environmental chamber pressure and layer thickness, were discussed to enhance the quality and reliability of L-PBF components. The research contributes valuable insights into understanding and addressing spatter-induced defects in additive manufacturing processes, emphasizing the importance of further investigations and machine learning applications for real-time process monitoring data.

Yin et al. [35] conducted a study to investigate the correlation between the quality of objects formed in laser powder bed fusion (LPBF) and the dynamics of spatter during the process. The research aimed to understand the mechanisms of defect generation in LPBF by examining the properties of the melt track and the behavior of spatter particles, utilizing in situ high-speed, high-resolution characterization techniques.

The study employed various tools, including a CMOS high-speed video camera, a pulsed high-power diode laser light source, and a zoom lens system for imaging. The camera setup angle was 45°, and image-filtering algorithms were applied to enhance edges and distinguish the boundary of the molten pool and spatter particles. Inconel 718 was used in the LPBF process, and morphological features of the samples were characterized using a laser confocal microscope and an optical microscope.

Key findings included the morphology of the LPBF melt track, which exhibited a hump-shaped protrusion at the head, a comparatively flat middle part, and a depressed shape at the tail. The study revealed that the head protrusion and tail depression significantly impacted the formation quality of printed objects. The correlation between ex situ melt track properties and in situ high-speed, high-resolution characterization of spatter dynamics was highlighted.

The ejection behavior of droplet columns at the rear of the molten pool was categorized into three stages: rising, quasi-steady-state, and falling stages. Parameters such as ejection velocity, ejection angle, and hemispherical protrusion radius varied over time during the ejection process. Inclination angles of the tail depression increased with higher laser power, and spatter particles were observed to be deflected and driven by vapor recoil pressure, forming a Λ -shaped plume.

In conclusion, the study provided insights into defect generation mechanisms in LPBF, emphasizing the significance of the head protrusion and tail depression of the melt track in influencing the formation quality of printed objects. The correlation between ex situ melt track properties and in situ spatter dynamics characterization enhances the understanding of LPBF processes and offers valuable insights for improving the quality of formed objects.

Rock et al [36] conducted a study focused on characterizing and analyzing self-organized patterned surface oxide spots on spatter particles generated during laser powder bed fusion additive manufacturing. Various techniques, including scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), transmission electron microscopy (TEM), and scanning transmission electron fine microscopy (STEM), were employed to describe these particles and comprehend their formation.

Experiments were conducted using a Concept Laser fiber MLab 100R LPBF machine with a 1080 nm YAG laser. Spatter particles with observed oxide patterning were collected from the powder bed after multiple LPBF runs, with experiments conducted under standard operating procedures and modified conditions to study the impact of chamber gas composition variations. Gas atomized 316 L stainless steel powder was used in both cases.

The study revealed that spatter particles exhibited diverse morphologies, including agglomerated, irregularly shaped, and spherical with dendritic microstructures. Some particles displayed highly spherical shapes with patterned surface features, characterized by periodic spotted surface arrangements, asymmetrical concentrated spots, and irregular shapes. Elemental analysis identified the presence of Si and Mn oxides on the spatter particle surfaces. Transmission electron microscopy (TEM) further characterized the spot cross-section, revealing complex features indicative of Si-Mn-O spot formation. The study also explored how different gas mixtures influenced the morphology of spatter particles.

In conclusion, the self-organized patterned surface oxide spots observed on spatter particles during laser powder bed fusion were attributed to the oxidation and solidification of liquid spatter droplets. The presence of silicon (Si) in the droplets led to the formation of silicates, which migrated to the surface and oxidized, resulting in the observed patterns. The study emphasized the significance of comprehending these formation mechanisms to optimize the LPBF process and enhance the quality of additively manufactured components.

Harithsa et al. [37] conducted a study on the influence of energy intensities on spatter and porosity evolution, microstructure, and mechanical properties in the laser powder bed fusion (LPBF) process of

AlSi10Mg. The study aimed to evaluate the effect of critical variables such as laser power, linear energy density, and volumetric energy density on pore characteristics, microstructure, and mechanical properties of the fabricated parts.

The methodology involved experiments using a Concept Laser M2 LPBF system with AlSi10Mg powder. Process parameters such as laser power, scanning speed, and hatching space were controlled and varied. Tensile specimens were tested, and their density and pore characteristics were analyzed using microscopy and image analysis. Scanning electron microscopy (SEM) was used for characterizing fracture morphologies.

Key findings from the study include the observation that pore quantities decrease with lower linear energy density, emphasizing the importance of energy input control to reduce porosity in LPBF. The microstructure of the molten pool is influenced by linear energy density, showing a decrease in depth with lower linear energy density. Mechanical properties, including ultimate tensile strength and elongation, are affected by scanning speed and linear energy density, with higher speeds resulting in decreased properties. Improved mechanical properties are linked to reduced pores, indicating that minimizing porosity enhances the fabricated parts' mechanical characteristics. Strong bonding in the molten pool is crucial for preventing external stress-induced destruction, with Si content influencing crack propagation. The distribution of Si near the boundary of deposited tracks affects powder recoating quality, leading to un-melted areas and the formation of holes and poor bonding inside the specimen. LPBF process parameters, such as laser power and energy densities, uniquely influence spatter and pore formation, microstructure, and mechanical properties.

In conclusion, the study underscores the significance of controlling energy intensities and optimizing process parameters to achieve the desired microstructure and mechanical properties in the LPBF process of AlSi10Mg.

Merve conducted [42] a study on the effect of spatter powder on the quality of IN939 parts fabricated using laser powder bed fusion. The methodology included fabricating IN939 samples using a metal 3D printer equipped with a fiber laser, with a feedstock prepared from virgin powder and 10 wt% spatter powder. A comparison was made between the structure and properties of parts produced from virgin powder and the mixture of spatter and virgin powder.

The study revealed significant differences between virgin and spatter powders in terms of morphology, particle size distribution, color, and the presence of oxides. The addition of spatter powder had notable effects on the surface roughness, density, and microstructure of the fabricated IN939 parts. The presence of re-melted and re-solidified particles in parts from the spatter-virgin powder mixture resulted in higher surface roughness and lower density.

The conclusion emphasized the negative impact of adding spatter powder to virgin powder on the quality of the fabricated IN939 parts. The study underscored the importance of understanding the structure and properties of spatter powder to enhance the material-process relationship in laser powder bed fusion.

Zhang et al. [45] conducted a study delved into understanding the influence of spattering on the surface roughness of in-process layers during laser powder bed fusion in additive manufacturing.

The methodology adopted for the study involved in-situ monitoring of spattering through the utilization of a vision camera and fringe projection profilometry. Additionally, a machine learning model was developed for spatter segmentation and feature extraction.

Results indicated a strong correlation between the spatter count and the processing regime, with laser power, scan speed, and hatching angle significantly impacting the spatter count. The study further demonstrated that monitoring and registering spatter could enhance the accuracy of predicting in-process layer surface properties.

In conclusion, the study emphasized that spatter monitoring and signature registration play a crucial role in more accurately predicting in-process layer surface properties. The spatter count was identified as a potential performance indicator for predicting surface properties, and the study suggested that implementing enhanced monitoring systems could provide more comprehensive spattering metrics for the effective prediction of part properties.

Avegnon et al. [39] investigated the formation of porosity in metal additive manufacturing, specifically within laser powder bed fusion (LPBF) systems. The research aimed to comprehend how the re-coater's position disrupted gas flow, leading to undesired pore formation. The study focused on unique porosity patterns formed on odd layers, exploring the relationship between re-coater position and convective heat transfer. By utilizing experimental techniques such as X-ray computed tomography (CT) and simulations with ANSYS Fluent software, the researchers analyzed porosity distribution and the impact of disrupted gas flow on heat transfer. Key findings included the disruptive effect of re-coater position during odd layers on gas flow, resulting in distinct cooling regimens for odd and even layers and contributing to the formation of keyhole defects. The porosity patterns observed aligned with print cells and re-coater position, forming a 45-degree pattern. Disrupted gas flow during odd layers led to regions with low gas velocity, causing heat retention at print cell boundaries and concentrated keyhole defects. The study underscored the importance of considering convection and gas flow in optimizing process parameters to minimize porosity in metal additive manufacturing.

Andani et al. [3] conducted an experimental study utilizing a computational image analysis framework and a high-speed camera to explore the phenomenon of pressure recoil leading to spatter formation and ejection during the Selective Laser Melting (SLM) process. The SLM 280HL machine, equipped with two 400-watt lasers and featuring a building chamber measuring 280mm x 280mm x 350mm, was employed for the experiments. Six test specimens were fabricated using both one and two lasers, with specimens 1, 2, 3, and 6 produced by a single laser and specimens 3 and 4 created by two lasers. The experimental conditions

included a laser power of 300 W, a layer thickness of 30 μm , and a scan speed of 1650 mm/s. The material utilized was AL-Si10-Mg, with an average size distribution of virgin powder ranging from 30 μm to 50 μm .

For image analysis, the researchers developed and employed Matlab code with the Otsu method. The results of this analysis revealed that a single laser beam produced 19 spatters, characterized by areas and diameters ranging from 0.02 mm^2 to 0.4 mm^2 and 120 μm to 620 μm , respectively. When both lasers were operating, the number of spatters increased to 34, with diameters ranging from 200 μm to 720 μm . Notably, a higher concentration of spatters was observed in the middle of the laser path, and the number of spatters in the 400 μm to 700 μm diameter range was greater when two laser beams were used.

In addition to image analysis, the researchers conducted tensile tests on the fabricated specimens and assessed their fracture behavior. The findings indicated that specimens manufactured using a single laser beam exhibited higher yield strength, fracture stress, and strain compared to those produced with two lasers.

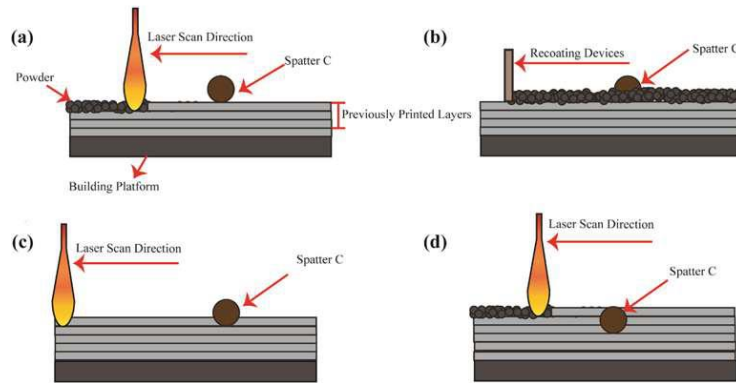


Figure 12. Sequence diagram of the manufacturing process in SLM 280HL machines [3]

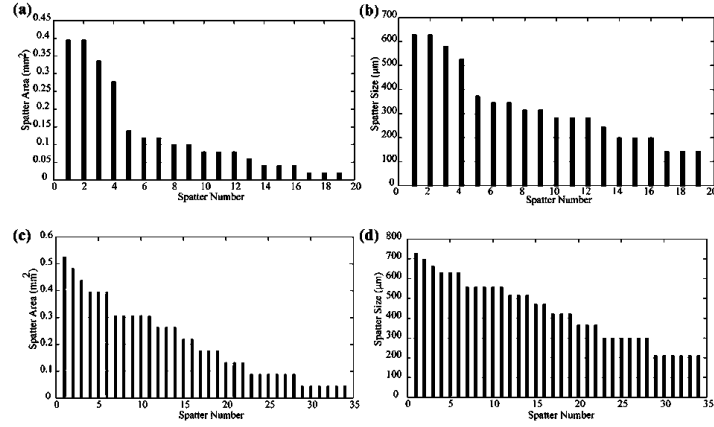


Figure 13. Spatter distribution inside a frame generated by a single laser beam (a, b) or two laser beams working closely together (c, d) [3]

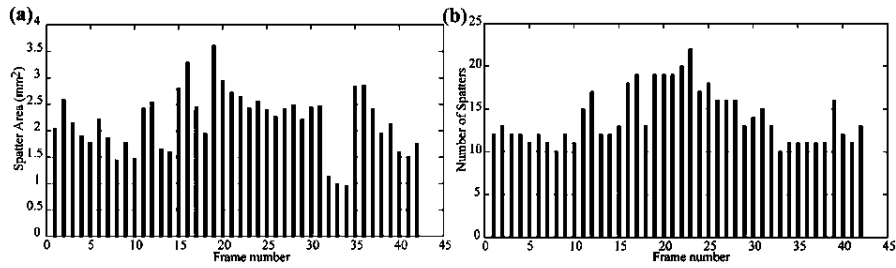


Figure 14. Spatter distribution [3]

Type	Yield Stress MPa	Fracture Stress MPa	Fracture Strain %
Sample made by one laser beam	215	350	3.85
Sample made by two laser beams	211	327	3.18

Table 1. Comparison of one and two beams for the mechanical properties

2.6 Inert Gas Flow

Bin Anwar et al. [5] conducted a review of papers focusing on the mechanisms behind spatter formation. Qiu et al. [6] employed high-speed imaging and modeling to conclude that Marangoni effects, combined with pressure generated by the expansion of vapor, were the primary causes of spatter ejection. Khairallah et al. [7] utilized a 3-dimensional high-fidelity powder-scale model to validate the results obtained by Qiu et al. [6]. Additionally, Bidare et al. [8] developed a finite element model simulating the inert atmosphere

and the laser plume to investigate the effects of varying laser speed and power. The study revealed backward ejection of particles in the opposite direction of the scanning when laser speed and power were high.

Researchers employed several computer models to study particle movement and fluid dynamics, utilizing Computational Fluid Dynamics (CFD) and a Discrete Phase Model (DPM). The turbulent $k-\epsilon$ model was applied, with the buoyancy force being neglected due to the low density of argon. DPM was used to track particle behavior within the flow field. The simulation was conducted using Ansys in a three-dimensional context. To reduce simulation costs, the top flow was neglected, as the powder bed was situated at the bottom, and it was assumed that the top flow had no significant impact. Mesh independence tests were performed using coarse, medium, and fine elements with maximum sizes of 10, 5, and 2.5 mm, respectively, via the cut cell method. The energy equation was excluded to avoid computation of natural convection. Inlet boundary conditions were set as a fully developed flow, while a vacuum pressure condition was applied at the discharge. A no-slip condition was specified for the plate surface. A medium mesh was employed as it yielded a maximum velocity of 1 m/s, while a fine mesh would have been significantly more time-consuming. The CFD analysis indicated flow circulation near the bed due to sharp edges in the discharge. Validation of size distribution performed via DPM showed a 0.6% error in region A and a 61% error in region C. The study's conclusion highlighted that larger spatter particles have lower initial velocities, resulting in shorter travel distances. The study aligned with experimental trends, although there were substantial differences in spatter diameter between the experiment and simulation, potentially due to the neglect of pressure recoil, contributing to 15% of spatter formation.

Alquaity and Yilbas [9] conducted numerical simulations of spatter trajectories within a chamber using an Eulerian Lagrangian approach. They considered various spatter sizes and angles, utilizing Ansys CFD Fluent to model the chamber, which had dimensions of 250 mm x 250 mm. Inert gas entered the chamber through 13 nozzles with a 12mm diameter. Inlet and discharge locations were set 67.5 mm above the base plate. The argon flow rate suggested turbulent flow conditions, and the $k-\epsilon$ turbulence model was employed.

Assumptions included incompressible flow, dry and non-reacting virgin powder and spatters, and spherical particle shape. Temperature effects were largely neglected as they were not considered to have a significant impact. A Discrete Phase Model (DPM) was used to model interactions between the inert gas and spatters. The study found that spatter size distribution ranged from 63 μm to 316 μm for a laser with 350 W of power and a scanning speed of 0.9 m/s, with the majority falling within the 80 μm to 110 μm range. The study assumed spatters were ejected from the center of the east edge of the base plate. Ejection angles were primarily between 20° to 40° for the same laser power and scanning speed, and these angles were considered in the study.

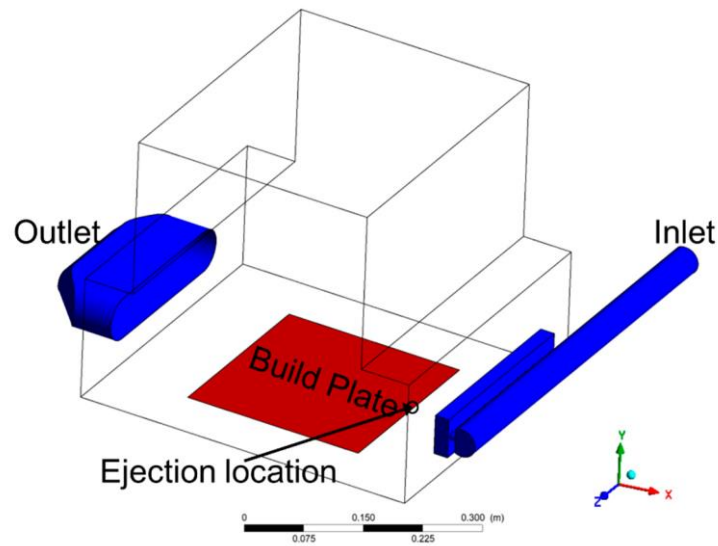


Figure 15. Diagram of the Renishaw AM250 chamber presenting the inlet, discharge, build plate, and ejection location. 250 mm x 250 mm square build plate [9]

The Navier-Stokes equations and the k-epsilon modeling equations were discretized using a second-order upwind scheme. Convergence criteria were established with a threshold of 10^{-4} for both the continuity and momentum equations. To optimize computational efficiency, six different mesh configurations were tested, ranging from 0.4 million to 5.8 million elements. It was observed that the velocity magnitude and discharge

velocity began to stabilize when the mesh consisted of 3.12 million elements, which was subsequently used for all subsequent simulations. Ejection velocities were calculated, and the Figure 18 illustrates the ejection velocity for various spatter sizes.

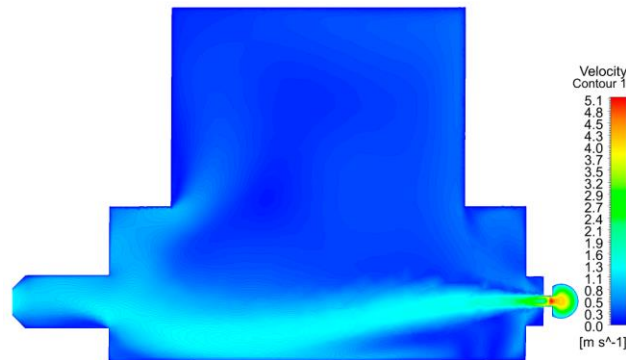


Figure 16. Velocity profiles across (XY plane) of the manufacturing chamber. Volume flow rate: 250 L/M [9].

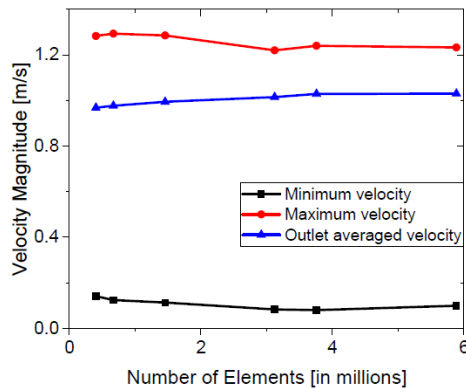


Figure 17. Grid stabilization test. Volumetric rate: 250 L/M, gas: air [9]

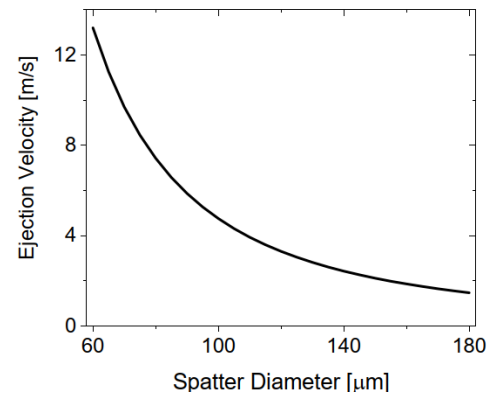


Figure 18. Spatter velocities as a function of spatter diameter [10]

The baseline design was subjected to simulation under an inert gas flow rate of 250 LPM. The Figure 19 illustrates the center plane of the simulation, where the maximum velocity reached 1.59 m/s. Alquaity analysis led to the conclusion that the non-uniform velocity profile would likely result in a higher

concentration of spatters in regions with lower velocities. Notably, the lowest velocity was situated at a distance of 30 mm, roughly midway between the base plate and the center of the nozzles (located 67.5 mm above the base plate).

Alqaity also determined that spatters with a size of 80 μm , ejected at angles of 20° and 40°, would exit the base plate. However, spatters with a size of 140 μm were expected to land on the base plate. Spatters sized at 110 μm were effectively carried away when the ejection angle was set to 40°. However, when the ejection angle was reduced to 20°, the flow was insufficient to transport these spatters, resulting in their retention within the system.

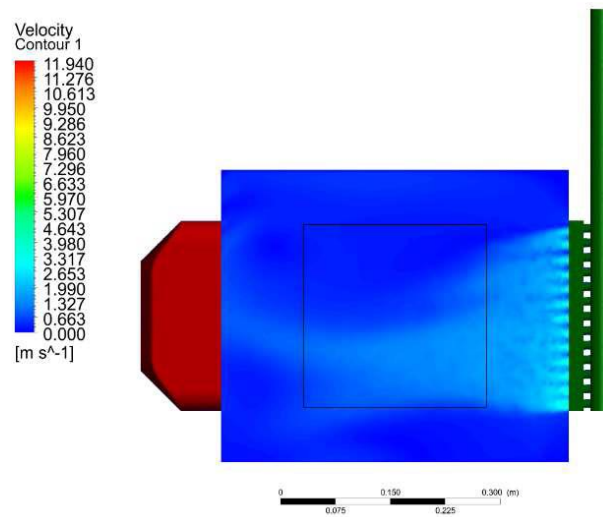


Figure 19. Center plane (XZ) showing velocity profile [9]

Alqaity and Yilbas [9] contemplated the use of smaller inlet nozzles based on their literature review, which suggested that smaller nozzles would lead to a more uniform velocity profile while maintaining the inlet flow rate at 250 LPM. In the modified design, the nozzles were reduced to a diameter of 6 mm. Simulation results for the modified design indicated that the maximum velocity reached 2.61 m/s, and spatter transport was significantly improved compared to the previous design.

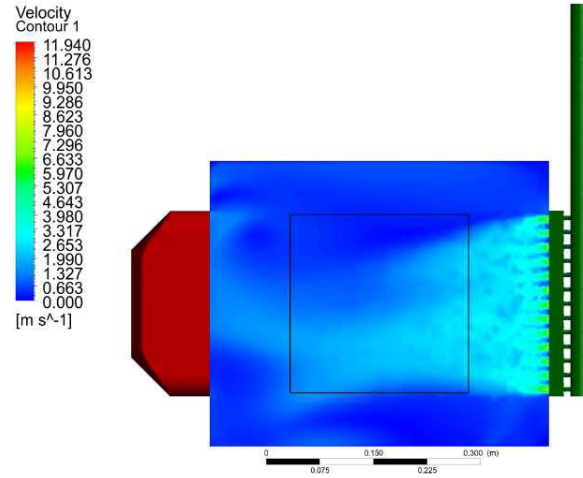


Figure 20. Center plane (XZ plane is 67.5 mm high) for the developed design showing the velocity profiles [9].

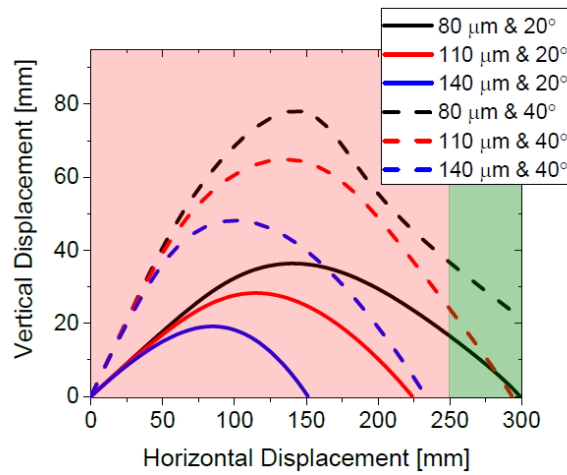


Figure 21. Spatter paths for base design. Red colored region represents the width of the base plate [9]

Chen [12] conducted several CFD simulations to optimize the flow using Ansys Fluent. He started by running a mesh independence test to determine the mesh size at which the velocity becomes independent from the mesh. Chen found that a mesh size of 3.5 million elements is independent of the mesh.

Chen then focused on the build plate plane and the region 3 mm above the build plate. He observed that the flow was not uniform, and his simulation results were consistent with those from Alqaity's [9] study. Chen

used the RENISHAW AM250 chamber in his model, which was the same chamber used in Alquaity's study [9].

Chen made various modifications to the chamber's design, such as changing the nozzle height and length, increasing the number of nozzles from 13 to 15, and extending the array width of the nozzles. His conclusions were that, extending the array width of the nozzles improved flow uniformity in the region 3 mm above the build chamber, lowering the nozzles resulted in a more uniform flow in the 3 mm region above the build plate. Figure 22, Figure 23, Figure 24, and Figure 25 illustrate the velocity contour for the base model, the model with lower nozzles, and the model with a wider array of 15 nozzles. These simulations helped Chen optimize the chamber's design for better flow uniformity.

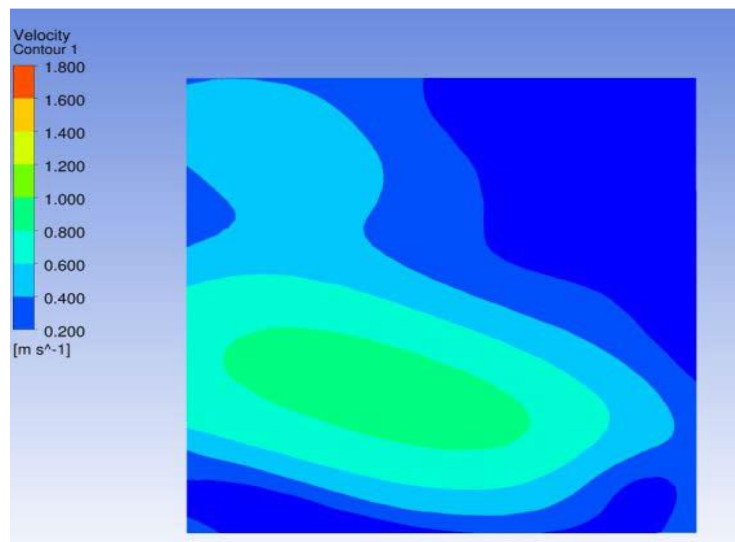


Figure 22. Base model 3mm plane above the build plate [12]

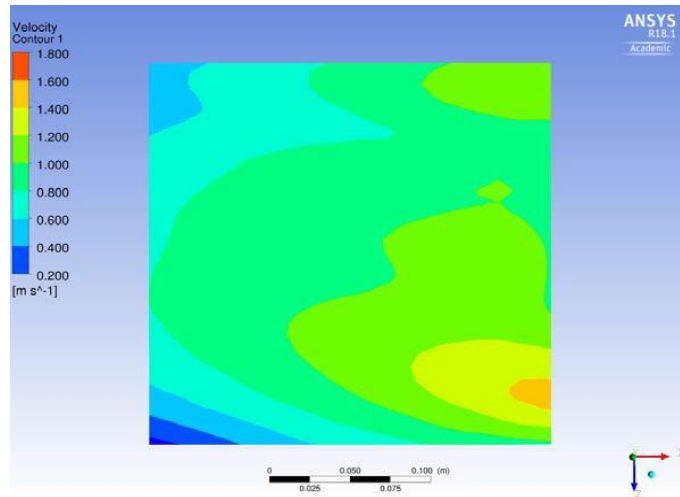


Figure 23. Lower nozzles 3mm plane above the build plate [12]

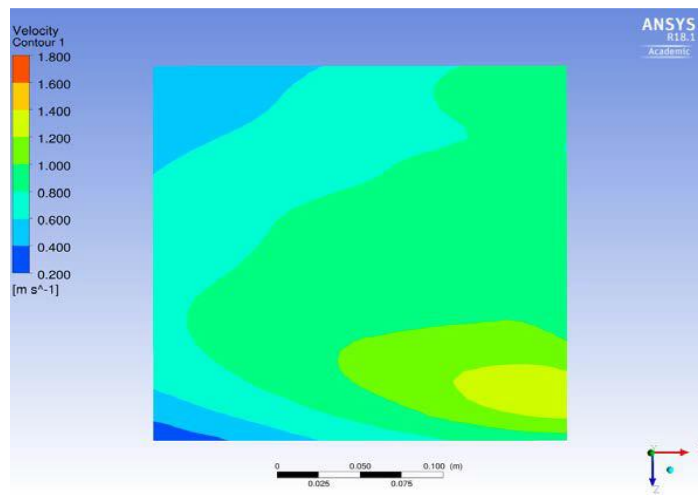


Figure 24. Lower and longer nozzles [12]

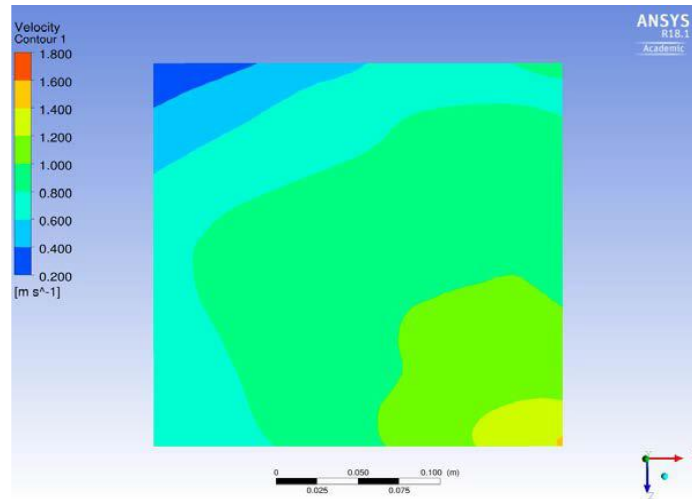


Figure 25. Extended array for the nozzles [12]

Pauzon et al. [28] conducted a study investigating the impact of helium addition to the process gas during laser powder bed fusion (L-PBF) of Ti-6Al-4V, specifically focusing on reducing the generation of incandescent spatter during the process. The study employed high-speed shadowgraphy imaging as a primary tool to observe and analyze the generation of spatters throughout the L-PBF process. In the experimental setup, collimated light illuminated the L-PBF process, and a high-speed camera captured the shadows of objects obstructing the light. The recorded images were subsequently subjected to analysis using image processing techniques. The key finding of the study indicated that the incorporation of helium into the process gas during L-PBF of Ti-6Al-4V resulted in a significant reduction in the generation of incandescent spatters. Comparative analysis revealed that both pure helium and the addition of helium to argon led to a reduction of incandescent spatters by at least 60% compared to the use of traditional argon alone. Notably, the quantity of colder spatters did not appear to be affected by the change in process gas flow. In conclusion, the study determined that the addition of helium to the process gas during L-PBF effectively reduces the generation of incandescent spatters. This reduction, amounting to at least 60%, was observed when using either pure helium or a helium-argon mixture in comparison to traditional argon alone. The study also emphasized the role of gas flow in dragging spatters and fumes downstream, acknowledging

that this dragging effect might be undesirable in certain configurations. Overall, the addition of helium to the process gas was deemed promising for enhancing the stability and quality of the L-PBF process.

Baehr et al. [21] investigated the removal of spatters in metal powder bed fusion through laser beam application, with a specific focus on the potential efficacy of various process gases such as argon and helium in alleviating spatter-related challenges. The comprehensive study encompassed theoretical considerations, experimental inquiries, and analysis of spatter distribution and characteristics. The methodology employed in the research encompassed both theoretical calculations and practical experiments. Theoretical considerations involved determining the maximum gas flow velocity for different gases based on particle pickup velocity, which set the threshold for particle removal from the powder bed. The potential of gas flow to eliminate spatters was evaluated using the Stokes equation for drag force. Experimental investigations utilized a unique in-situ spatter collection device. The experiments, conducted in a Trumpf TruPrint 3000 process chamber with a build platform cover, analyzed spatter distribution qualitatively through optical analysis and quantitatively by collecting and weighing spatters. Spatters were further characterized by size and shape through dynamic image analysis and selective electron microscopy. The methodology also included maintaining constant process parameters, measuring gas flow velocity, and analyzing the surface roughness of processed parts. The study's findings highlighted the significant impact of gas flow velocity and the type of gas on spatter removal during the powder bed fusion process. Notable conclusions included: Gas flow velocity influenced the force applied to spatters, with higher velocities resulting in increased force and improved spatter removal. The type of gas used affected spatter removal, with ArHe30 gas demonstrating superior results compared to pure Argon gas, resulting in fewer spatters accumulating on the powder bed. Spatter size distribution varied based on the gas used, with ArHe30 gas leading to a shift towards smaller particle sizes compared to Argon gas. The weight of collected spatters was influenced by the gas type, with ArHe30 gas resulting in lower spatter weight compared to Argon gas. Overall, these results underscored the significant role that gas selection and optimal gas flow velocity could play in addressing spatter-related challenges in the powder bed fusion process.

Cheng-Yen Chien [40] conducted a study investigating the interactions between gas flow and spattering phenomena during the laser powder bed fusion process of Inconel 718. The methodology employed a coupled Computational Fluid Dynamics (CFD) - Discrete Element Method (DEM) numerical simulation framework. Initial conditions were obtained through pure CFD simulations and high-speed CMOS camera observations. The simulated landing locations were validated with experiments and published data. The study successfully validated simulated landing locations with experimental data and compared numerical results with experimental observations. The conclusion highlights that the proposed coupled CFD-DEM simulation framework effectively captures the interaction between flow dynamics and spatter dynamics in the laser powder bed fusion process. Additionally, the study observed that a greater number of large particles land on the powder bed close to the scan track, while only a few large particles land on the powder bed further from the track.

In a study conducted by Zeng et al [13], the primary objective was to optimize the removal efficiency of process emissions within the Selective Laser Melting (SLM) process. The investigation primarily centered on designing the gas flow system, examining key variables such as gas inlet width, inlet height, volume flow rate, and the materials involved in the process. The aim was to enhance the overall effectiveness of emission removal in SLM. Zeng utilized the Renishaw AM250 3D model to simulate argon flow using Ansys software. The study also involved employing a discrete phase model to track particles, using five evenly distributed lines over the build plate instead of individual spatter definitions. Ejection angles of 60°, 90°, and 120° were selected for the simulation. The material under investigation was SS316L with a density of 7950 kg/m³, with particle diameters ranging from 20 to 80 µm. Argon was chosen as the inert flow, with a set mass flow rate of 0.00677 Kg/s (equivalent to 250 L/min). Convergence criteria were established at 1×10^{-4} for continuity and momentum. The study's findings indicated that increasing the flow rate to 500 L/min significantly improved spatter removal. Moreover, aligning the width of the inlet nozzles array with the build plate proved more effective in the removal process, and lower nozzle heights demonstrated better penetration of spatters in the lower region. The studies by Ferrar et al., Anwar & Pham, [14,15]. Collectively

emphasize the influence of gas flow on the physical characteristics and structural integrity of the printed material. They shed light on how poor gas flow can lead to higher porosity, decreased compressive strength, and various defects, such as lack of fusion, induced by the by-products of laser melting. Zeng et al [18], proposed design to improve spatter removal efficiency is the counter-Coanda effect inlet system design. This design includes an additional row of nozzles placed directly under the primary inlet nozzles. The supplemental gas flow from the secondary nozzles helps to improve the pressure level of the low-pressure zone under the main velocity stream, reducing the Coanda effect. This design has been shown to efficiently enhance the spatter clear rate, increasing it from 69% to 93%. Additionally, the implementation of elongated inlet nozzles in the counter-Coanda effect design further improves the clear rate to 95%.

Philo et al.'s work [16], on the other hand, introduces the capability of Computational Fluid Dynamics (CFD) in predicting and evaluating gas flow inside the AM250 machine. Their research not only showcases the potential of CFD but also underlines the sensitivity of flow uniformity to specific design parameters, such as gas inlet rail diameter and nozzle shape.

The collective findings from these studies underscore the critical role of gas flow in the additive manufacturing process and its impact on the quality of the final product. They reveal a gap in understanding the underlying mechanisms and specific design guidelines for achieving optimal gas flow within the chamber. This gap in knowledge, as highlighted by these previous studies, becomes the driving force behind my research to delve into the intricate fluid dynamics within the RENISHAW AM250 chamber. This study aims to fill this void by exploring the gas flow intricacies and, through a systematic optimization process, derive comprehensive design guidelines to enhance gas flow efficiency within the chamber. This approach not only builds upon existing knowledge but also seeks to provide practical and step-by-step recommendations for improving gas channels, offering valuable insights for the optimization of the AM250 machine's performance in additive manufacturing.

Philo et al [17] also conducted a comprehensive study analyzing the impact of gas flow inlet design on the Renishaw AM250 laser powder bed fusion machine through computational modeling. The primary objective was to comprehend the gas flow dynamics across the build platform and assess how design alterations influence flow uniformity, local gas velocity, and accumulation of spatter particulates. The study validated the computational model using Hot Wire Anemometer (HWA) testing and also investigated the removal of by-products from the process zone, ultimately aiming to offer insights and design considerations for future generations of additive manufacturing machines.

The study's findings hold crucial implications for the development of future additive manufacturing machines. Focused on the gas flow inlet design of the Renishaw AM250, the research explored the effects of adjusting inlet design parameters. Reductions in the inlet rail radius, as well as lowering inlet and discharge heights, notably enhanced flow uniformity, average flow velocity, and minimized spatter accumulation on the processing area. These design changes resulted in a remarkable 21.05% increase in flow uniformity and a substantial 26.64% reduction in spatter accumulation. The significance of gas flow in the additive manufacturing process was underscored by the study's findings. Inconsistent gas flow can introduce variations in mechanical properties and build quality. Consequently, future generations of additive manufacturing machines should prioritize optimizing the gas flow system to ensure even flow distribution and efficient by-product removal. This enhancement can significantly improve component homogeneity across the build platform and elevate overall build quality. Moreover, the study highlighted the pivotal role of computational modeling, particularly Computational Fluid Dynamics (CFD), in comprehending and refining the additive manufacturing process. Employing validated CFD models, designers and engineers can explore various design parameters, enabling informed decisions to enhance the performance of additive manufacturing machines. Overall, the findings presented valuable design considerations for future machines, aimed at enhancing their efficiency and the quality of production.

2.7 Type of Spatters

Young et al. [11] conducted a comprehensive series of experiments to investigate the characteristics and formation processes of spatters. Their research identified five distinct types of spatters, each with unique characteristics:

1. **Solid Spatter:** This type of spatter results from the forces exerted by the vapor jet on un-melted powder particles, leading to their ejection.
2. **Metallic Jet Spatter:** Metallic jet spatter is generated due to pressure recoiling in the depression zone. The spatter becomes detached from the melting pool and solidifies during ejection.
3. **Powder Agglomeration Spatter:** In this type of spatter, powders and spatters agglomerate and consolidate, resulting in spatters significantly larger than the original source powder. Two common subtypes of powder agglomeration spatter are liquid-solid powder agglomeration and liquid-liquid powder agglomeration.
4. **Entrainment Melting Spatter:** Entrainment melting spatter occurs when ambient gas flow transports solid particles into the laser heating area. When these entrained solid particles come into contact with the laser beam, they melt and are expelled by the vapor jet. In some cases, these melting entrained particles may collide and combine, leading to entrainment melting spatter.
5. **Defect-Induced Spatter:** Defect-induced spatter occurs when the laser encounters significant imperfections within the component, such as large pores. The interaction between the laser and these large pores results in an abrupt instability, leading to the creation of distinct liquid spatter. Possible mechanisms for defect-induced spatter include the rapid expansion of trapped gas within the pore and the rapid change in absorbed laser energy due to multiple reflections within the pore.

Young et al.'s experiments revealed that solid spatter was observed across all laser powers and scanning speeds. However, metallic jet spatter was found within a specific range of laser power and scan speed. By reducing the laser power or increasing the scan speed beyond a particular threshold, the generation of

metallic jet spatter was eliminated. Reduced laser power (less than 364 W) or increased laser scan speed (higher than 1 m/s) reduced the input energy density, rendering the vapor jet and melt flow insufficient to create metallic jet spatter. Additionally, reducing the scan speed below 0.3 m/s eliminated the generation of metallic jet spatter for AlSi10Mg.

The researchers concluded that there are five distinct types of spatters, with powder agglomeration spatter exhibiting the largest size. The key influencing parameters on spatter formation are laser power, scan speed, and environmental pressure.

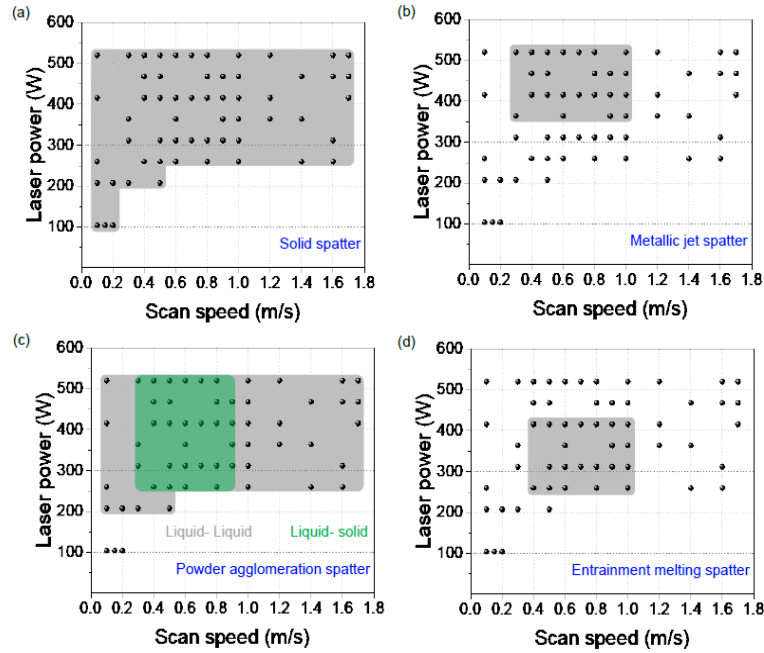


Figure 26. Graphs spatter initiation under various process parameters (spatter formation map) (spatter formation map). (a) Rigid spatter. (b) Metallic jet spatter. (c) Powder agglomeration spatter. (d) Entrainment melting spatter. It is made of AlSi10Mg. The parameters that were tested are shown by black dots. The shaded areas show where a certain kind of splatter was seen. All outlines are based on observations of spatter from testing at certain processing conditions. They have not been tested as thresholds or absolute limits of where the different types of spatter can form [11].

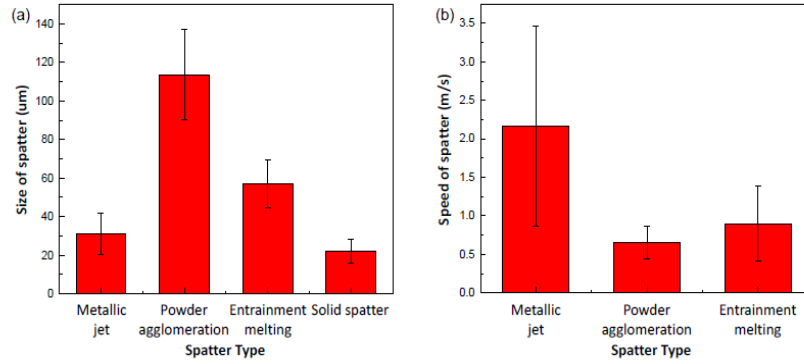


Figure 27. Spatter initiation graphs for different process settings (spatter formation map) (spatter formation map). Stiff splatter, a. Spattering metal from a jet engine. C) Spatter caused by the agglomeration of powder. Spattering caused by entrainment during melting (d). The material used is AlSi10Mg. Black circles depict the tested parameters. The areas with shading denote the presence of specific types of spatters. All contours were derived from observations of spatter during testing under specific conditions of processing. They have not been thoroughly examined as potential limits or thresholds for the various spatter types [11].

CHAPTER 3

NUMERICAL STUDY

In the base model, the introduction of inert gas flow is accomplished through 13 nozzles that are connected to a header, resembling a manifold. To assess the impact of various geometrical changes, Ansys Fluent is utilized to simulate each of these modifications. A crucial aspect of this simulation study is the determination of mesh independence, which ensures that the computational mesh provides reliable and accurate results. The findings from the mesh independence study indicate that a mesh with a 5 mm element size, featuring refinement in the 13 nozzles, inlet, and discharge, is the optimal choice, striking a balance between accuracy and computational cost.

The study encompasses multiple mesh configurations, including 10 mm, 7.5 mm, 5 mm, 4 mm, 5 mm with refinement, and 4 mm with refinement. The primary performance metric evaluated is the average velocity in the center plane. This metric is calculated and plotted against the number of mesh elements for each configuration. The analysis aims to identify the mesh size that provides accurate results while keeping computational costs manageable.

Once the optimum mesh configuration is determined, the study progresses to the introduction of spatters into the chamber. This is done for both the final design, incorporating the selected geometrical changes, and the base design without modifications. The goal of this step is to verify and assess how the inert gas flow enhancements in the final design impact the removal of spatters in comparison to the base design. This validation process ensures that the proposed modifications indeed lead to improved spatter removal efficiency within the build chamber.

3.1 Assumptions:

The flow inside the chamber is considered turbulent based on the inert gas velocities used and therefore $k - \epsilon$ turbulent model was used for the investigation. The turbulent flow is modeled as steady flow to capture the average flow dynamics within the build chamber.

3.2 Governing Equations:

The turbulent flow governing equations are described below.

3.2.1 Continuity equation:

$$\nabla \cdot \vec{v} = 0 \quad (1)$$

3.2.2 Momentum equation:

Continuity equation:

$$\nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \mu \nabla^2 \vec{v} \quad (2)$$

Momentum equations:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial}{\partial x_i} \right] + G_k + G_b - \rho \epsilon \quad (3)$$

$$\frac{\partial}{\partial t}(\rho \epsilon) + \frac{\partial}{\partial x_i}(\rho \epsilon u_i) = \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_i} \right] + C_{1\epsilon} \frac{\epsilon}{k} C_{3\epsilon} G_b - \rho C_{2\epsilon} \frac{\epsilon^2}{k + \sqrt{\nu} \epsilon} \quad (4)$$

The generation of the turbulent kinetic energy due to the mean velocity is express by G_k , while G_b is the turbulent kinetic energy caused by buoyancy. The turbulent Prandtl numbers for ϵ and k are represented by σ_k and σ_ϵ respectively. $C_{1\epsilon}$, C_2 , and $C_{3\epsilon}$ are constants whose default values given for the Realizable k- ϵ model in ANSYS Fluent were used.

The realizable $k - \varepsilon$ model, as described in the provided text, represents a more recent development in turbulence modeling. It introduces two significant changes compared to the standard $k - \varepsilon$ model:

1. Turbulent Viscosity Formulation:

The realizable $k - \varepsilon$ model features a new formulation for the turbulent viscosity. This is a key parameter in turbulence models that influences the transport of turbulent kinetic energy k and dissipation rate ε .

2. Dissipation Rate Transport Equation:

A new transport equation for the dissipation rate ε , is derived from an exact equation for the transport of the mean-square vorticity fluctuation. This introduces a more accurate representation of the dissipation process in turbulent flows. The term "realizable" in the context of the model implies that it satisfies specific mathematical constraints on Reynolds stresses, aligning with the physics of turbulent flows. Notably, neither the standard $k - \varepsilon$ model nor the RNG $k - \varepsilon$ model is realizable. An immediate advantage of the realizable $k - \varepsilon$ model is its improved prediction of the spreading rate in various flow scenarios, such as planar and round jets. Additionally, it is expected to offer enhanced performance in flows featuring rotation, boundary layers subjected to strong adverse pressure gradients, separation, and recirculation.

Force balance equations:

$$\frac{d\vec{u}_p}{dx} = F_D(\vec{u} + \vec{u}_p) + \frac{\vec{g}(\rho_p - \rho)}{\rho_p} \quad (5)$$

The force balance equation describes the particles interaction with the inert flow.

Drag force:

$$F_D = \frac{18\mu}{\rho_p d_p^2} \cdot \frac{C_D Re}{24} \quad (6)$$

Relative Reynolds number:

$$Re = \frac{\rho d_p |\vec{u}_p - \vec{u}|}{\mu} \quad (7)$$

Drag Coefficient:

$$C_D = b_1 + \frac{b_2}{Re} + \frac{b_3}{Re^2} \quad (8)$$

The drag coefficients are taken from Morsi et al. [19].

3.3 Geometrical Changes

Numerous geometric changes were explored to enhance the inert gas flow profile within the chamber. These changes included varying the length of the inlet nozzles, adjusting the discharge cross-sectional areas of the nozzles, altering the incline, modifying the header diameter, considering the number of headers, and introducing changes such as the orifice plate and fillet. Each of these alterations had specific parameters that influenced the flow profile.

To determine the most effective change in each category, a series of iterations were carried out. For changes involving the length of the inlet nozzles, varying the discharge cross-sectional areas of the nozzles, incline, and fillet, multiple iterations were conducted to pinpoint the optimal adjustment that would positively impact the flow profile. In contrast, changes related to header diameter, the number of headers, and orifice locations, sizes, and inner diameters were evaluated to understand their effects for potential future investigations.

In the simulation process, a convergence criterion of 10^{-3} was applied to x, y, and z velocities, as well as for continuity, k, and epsilon, while monitoring the average discharge velocity. Two cases with different boundary conditions were set for the inlet, with argon flow. The first boundary condition was 5 m/s and the second boundary condition was 10 m/s. Upon completing all the simulation, a single change in

geometry from Table 2 was introduced and investigated. Upon completing the simulation, the profiles were carefully studied in terms of the location, skewness, and velocity magnitude. For instance, incline modification has 3 angles as shown in Table 2. Each angle was simulated and studied to see the effect on the flow and after finishing the 3 angles, one angle was selected for the final design based on the effect on the flow profile.

Varying the length of the inlet nozzles (mm)	Varying discharge cross sectional nozzles (mm)	Incline (°)	Fillet Radius (mm)	Fillet Radius one side (mm)
1.5	10	25	0.25	2
2	11	30	0.5	1.5
2.25	11.5	35		0.5
2.5		35.69		
		64.2		

Table 2. Geometry changes parameters.

3.3.1 Base model

Base model is Renishaw AM250, the build plate size is 250mm x 250mm and it consist of 13 inlet nozzles with diameter of 12mm and length of 30mm connected to 1 header with diameter of 39mm. The base model is shown in Figure 28.

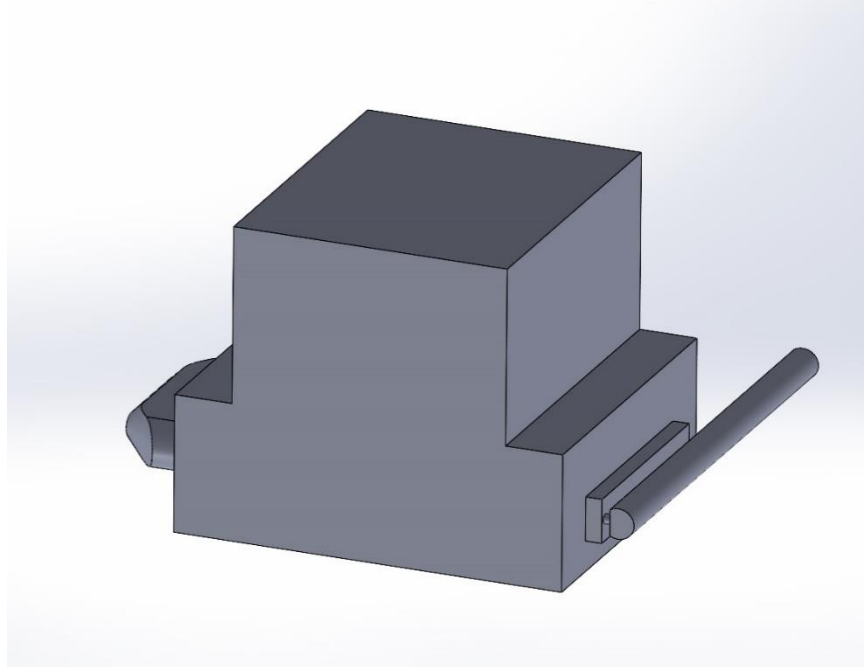


Figure 28. Base model.

3.3.2 Varying nozzle length

In the base design, the nozzle length is 30 mm. Despite the fact that all the nozzles have the same dimensions and are positioned at the center of the chamber, the flow profile is shifted towards the right. This observation suggests that adjustments are needed, such as changing the diameter or length of the nozzles on the right or left side, to balance the flow profile and shift it towards the center of the chamber.

To address this, variations of 1.5 mm, 2 mm, 2.25 mm, and 2.5 mm between the nozzle and the next one was applied to achieve a more balanced flow profile. Figure 29 illustrates how this change in the geometry.

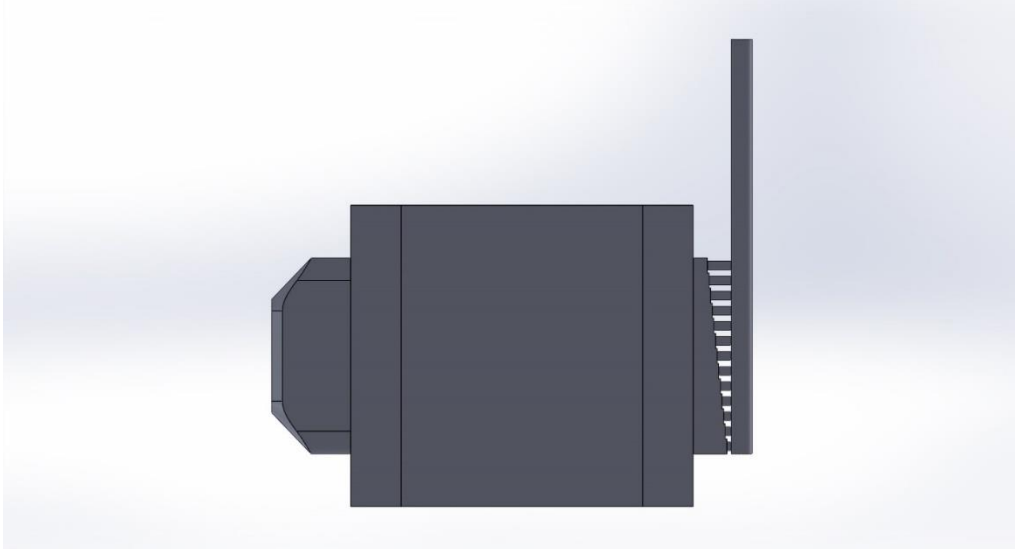


Figure 29. Varying nozzle length.

3.3.3 Varying discharge cross sectional area

In this modification, the areas of the discharge for the 13 nozzles were varied. 3 diameters of the discharge area for the first nozzle were implemented, and the last nozzle maintained the 12mm. for example, 10 mm first nozzle with last nozzle being maintain as is (12mm), the variation between the first and last one would:

$$d_v = \frac{(d_{n13} - d_{n1})}{12} \quad (9)$$

d_v is diameter variation between the nozzle and the next.

d_{n13} is the last nozzle diameter.

d_{n1} is the first nozzle diameter.

For 10 mm case, $d_v = \frac{12-10}{12} = 0.167 \text{ mm}$. Adding this value to the next nozzle, yields 10.167mm for nozzle number 2. Adding this value to the next nozzle number 3, diameter yields 10.33mm and so on until reaching 12 mm to nozzle number 13. All three cases are illustrated in Table 3.

Nozzle Diameter (mm)			Nozzle Position
11.5	11	10	1
11.54	11.08	10.17	2
11.58	11.17	10.33	3
11.62	11.25	10.50	4
11.67	11.33	10.67	5
11.70	11.42	10.83	6
11.75	11.50	11.00	7
11.79	11.58	11.17	8
11.83	11.67	11.33	9
11.87	11.75	11.50	10
11.92	11.80	11.67	11
11.95	11.91	11.83	12
12.00	12.00	12.00	13

Table 3 Inlet nozzle discharge variation

10mm, 11mm and 11.5 mm were tested for the first nozzle. The 10mm and 11 mm moved the flow to the extreme left while 11.5 mm shifted the flow slightly to the left. This could be a result of the pressure variation in the discharges of the 13 nozzles where the last nozzle discharge pressure is the highest. Figure 30 shows the 3D model of the nozzle's discharges.

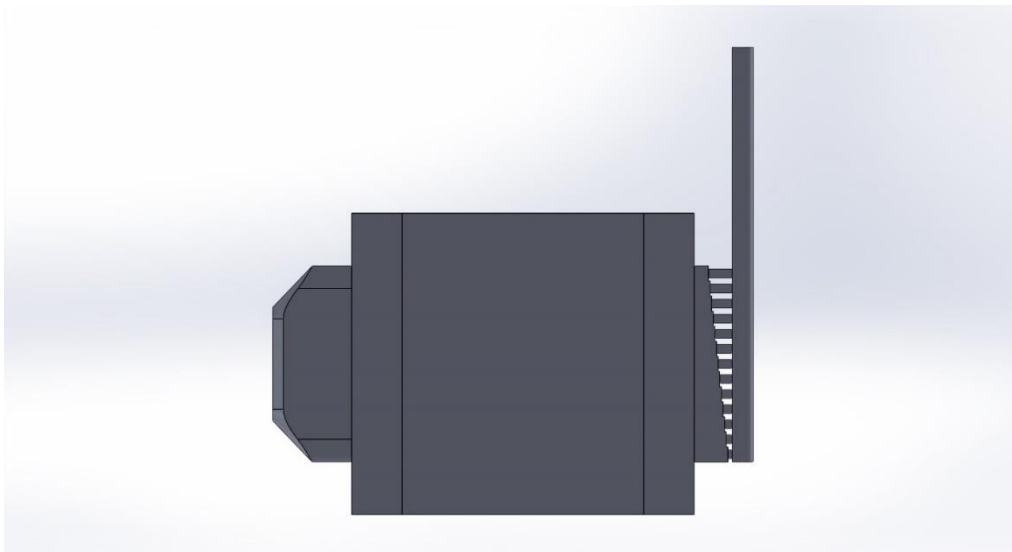


Figure 30. Varying nozzle length.

3.3.4 Incline angle

The base model exhibits a step change in geometry after the inlet nozzles discharge. This feature can be leveraged to enhance the removal of spatters in the lower regions of the chamber. In Figure 52, the flow in the XY plane at the center shows that the flow travels a significant distance before reaching the lower region. Since the height of the nozzle is 67.5 mm, in the near regions to the nozzle, the flow does not interact with the spatters. Therefore, introducing an incline should help improve the flow in the lower region as there will be no separation between the chamber and the flow. Figure 31 illustrates the modification of the incline. The key parameter considered in this modification is the angle of the incline. In this study, inclines of 41.53° , 45° , and 55° were introduced and simulated. The 41.53° is specific because of the re-coater's location which limits the incline, and a less steep incline cannot be introduced on the Renishaw AM 250. A 35 mm distance between the incline and the center of the build plate must be maintained to ensure that the incline does not interfere with the re-coater.

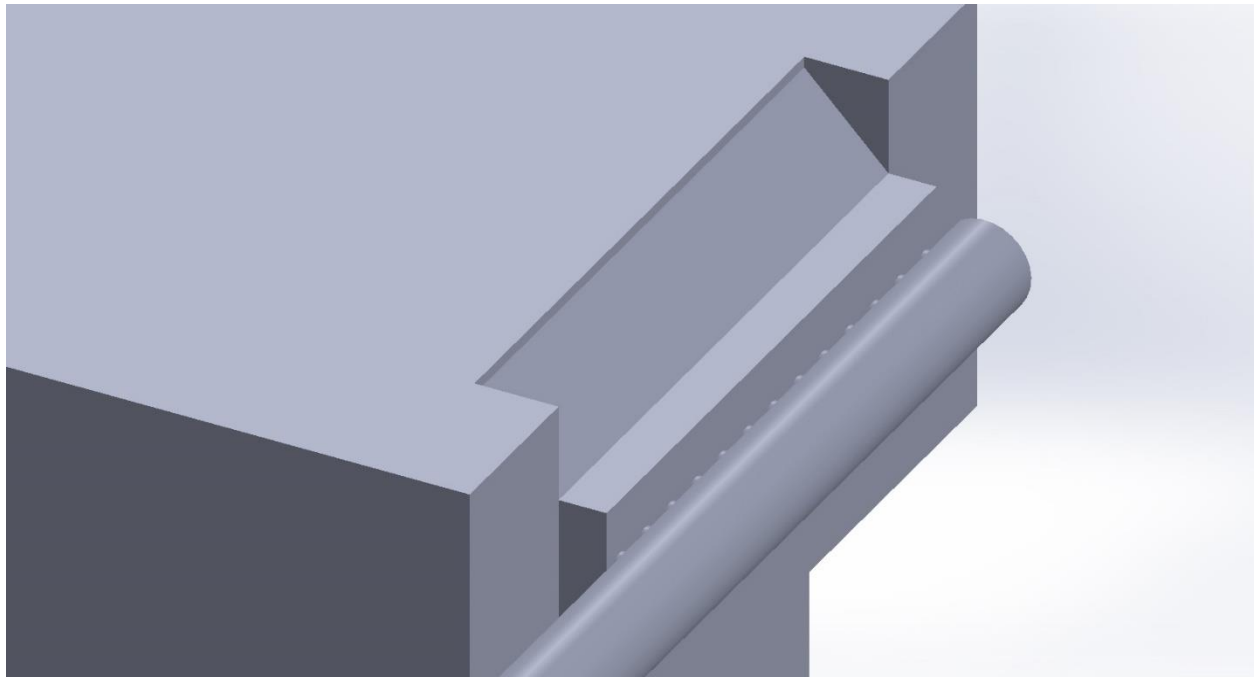


Figure 31. Incline with 45° angle, 3D model.

3.3.5 Fillet

Introducing fillets to the design is a key modification to improve the flow characteristics within the chamber. The use of fillets helps eliminate the sharp corners that can disrupt the flow and create boundary separations. Two types of fillets were introduced in the study, each targeting specific areas of the design.

- 1- One-Side Fillet: This fillet is applied at the junction between the header line and the nozzles. It helps to smooth out the transition in this area and reduce flow disturbances.
- 2- Two-Side Fillet: The two-side fillet is introduced at the junction between the header line and the nozzles, as well as at the junction between the chamber and the nozzles. This fillet extends its benefits to both of these critical areas and aims to further improve flow uniformity and eliminate boundary separations.

The key parameter in these fillets is the radius, which determines the extent of smoothing and transition improvement. The study evaluated different radius values to determine the most effective fillet design for optimizing flow characteristics in the chamber. These fillet modifications are important for achieving a more even and efficient flow of inert gas to enhance spatter removal.

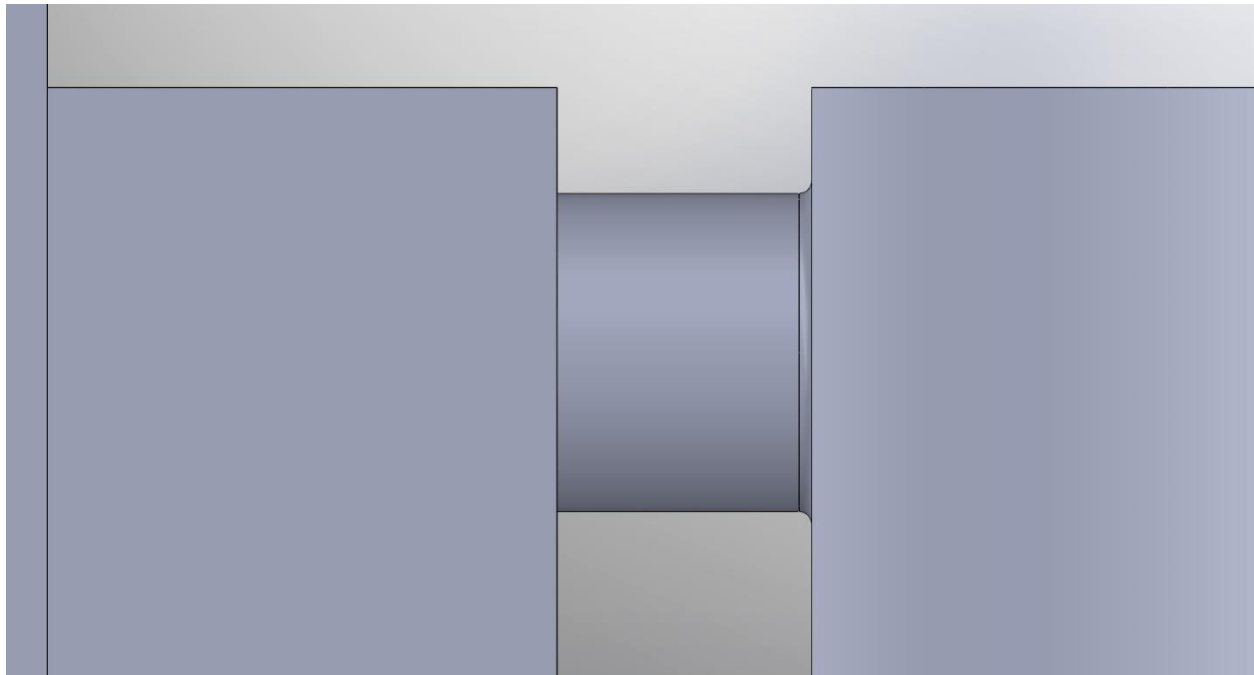


Figure 32 One side fillet with radius 0.5mm.

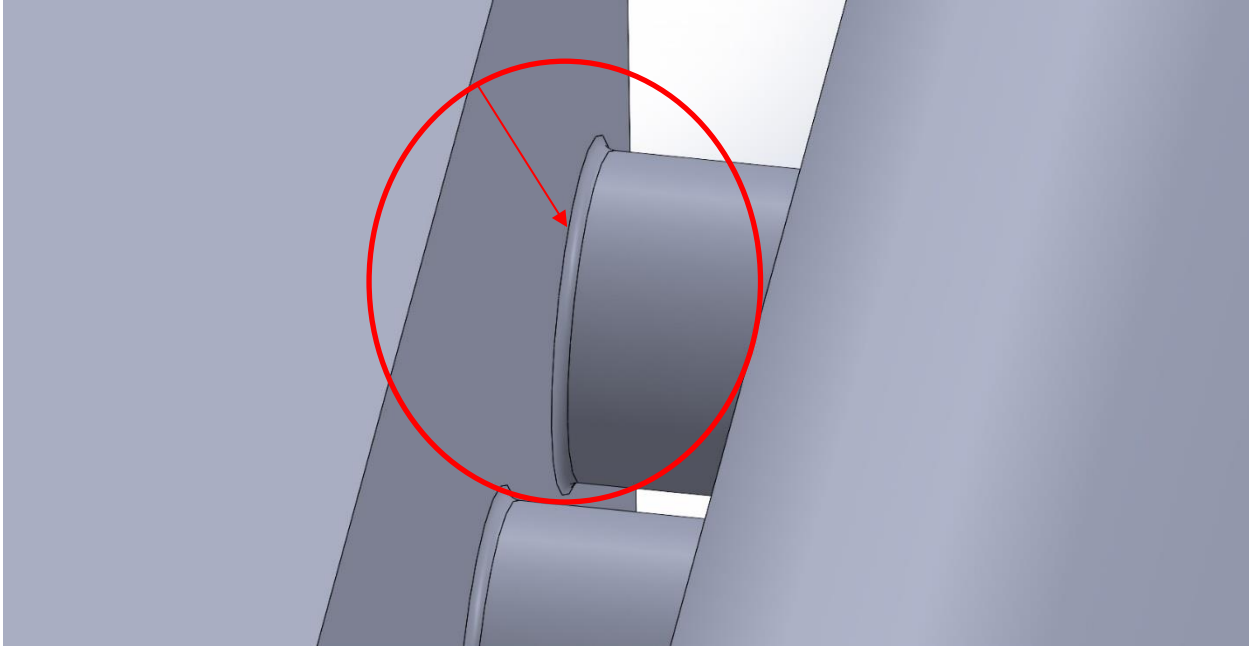


Figure 33. Zoomed in fillet, arrow indicates the location of the fillet (between the nozzle discharge and build chamber).

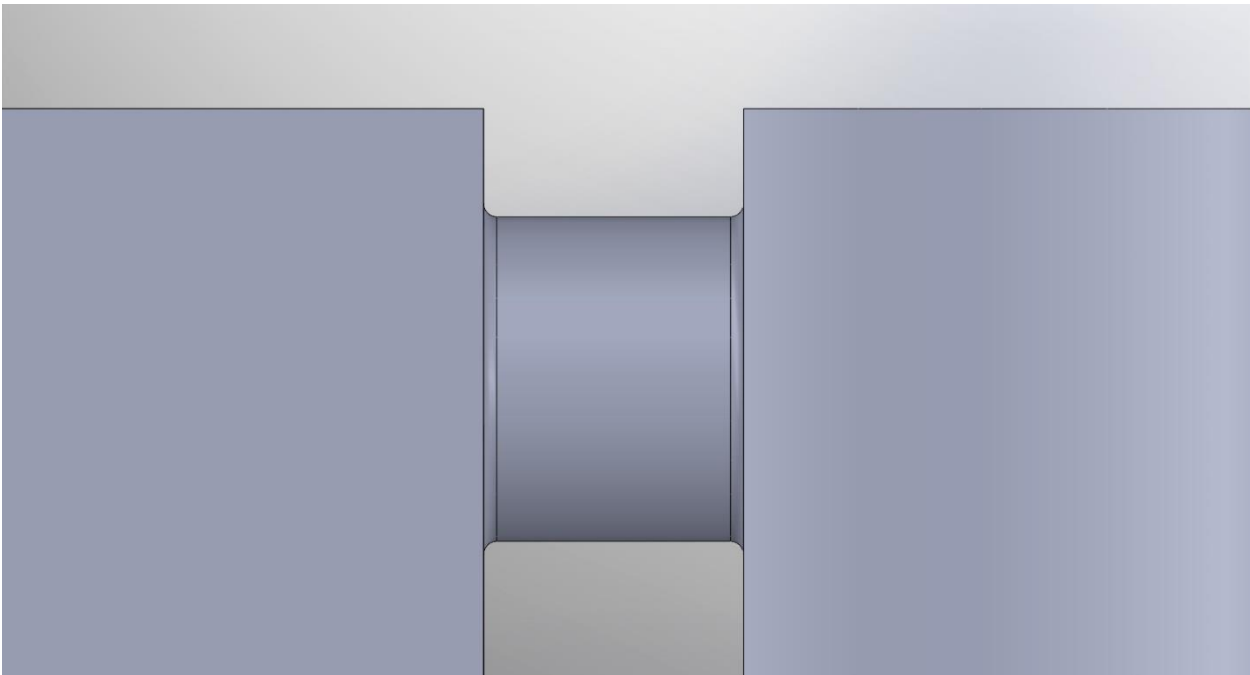


Figure 34. Two sides fillet with radius 0.5mm.

3.3.6 Inlet header

Given the asymmetry and off-center flow profile observed in the previously illustrated base model, the exploration of modifications to the inlet header for a symmetrical configuration is a worthwhile investigation. In this adapted model, an additional inlet header, precisely mirroring the length, diameter, and shape of the base model, was introduced.

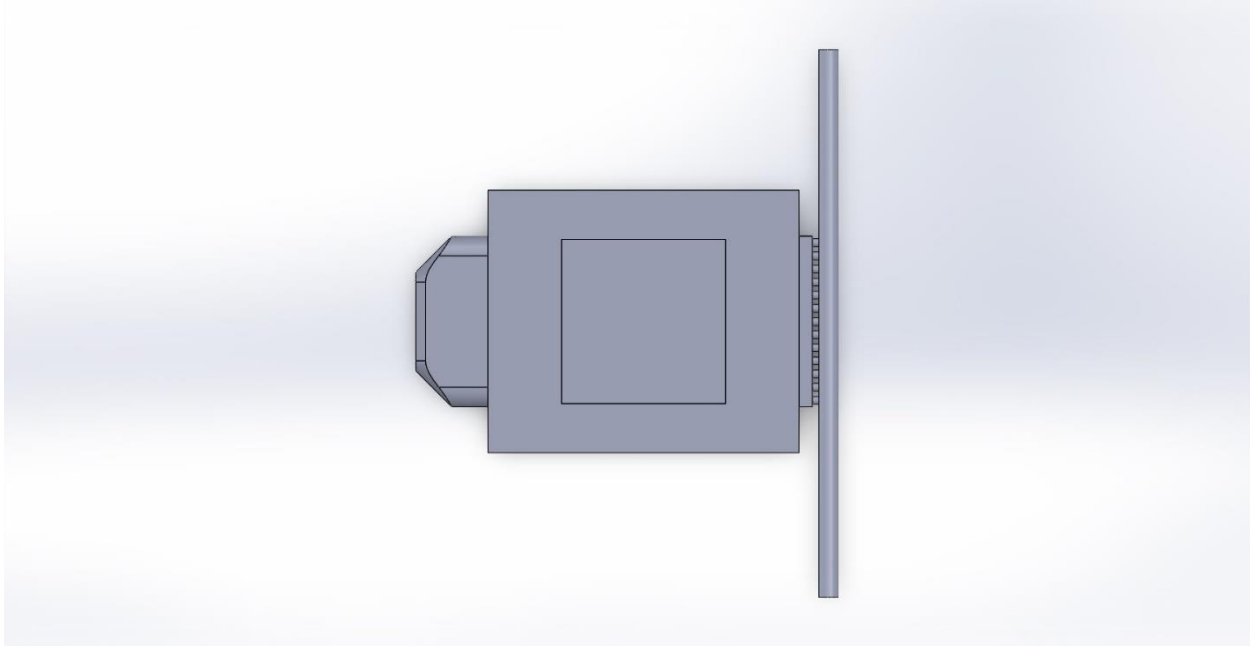


Figure 35. Base model with two inlet headers 3D model.

3.3.7 Final design

Three design modifications were chosen for the final iteration. These modifications encompassed variations in nozzle length, nozzle discharge configuration, and nozzle incline. In an effort to mitigate nozzle separation and promote flow uniformity, a fillet was considered, but it was ultimately excluded from the final design. The exclusion was driven by the fact that fillet increased the skewness ultimately reducing the uniformity of the flow. Table 4 provides an overview of the final design alternatives explored in this study.

Final design	Varying nozzles discharge cross sectional area (mm)	Varying the length of the inlet nozzles (mm)	Incline (°)
1	10	2.25	35.69
2	11	2.25	35.69
3	11.5	1.75	35.69
4	11.5	1.5	35.69

Table 4 Final design changes.

Design 1 featured several modifications, including 10mm starting discharge nozzles, a 2.25mm varying nozzle, and a nozzle incline of 35.69°. All four designs aimed to improve flow uniformity, with a focus on the central region over the build plate.

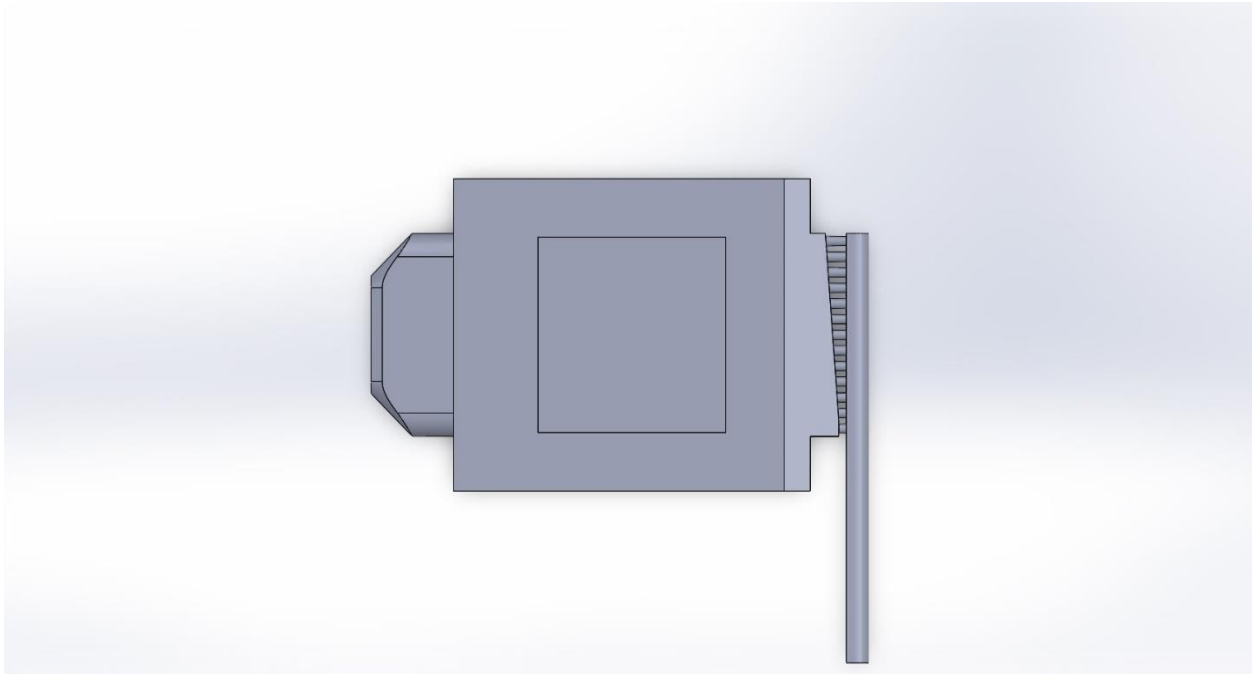


Figure 36. Final design.

3.4 Discrete Phase Model

Andani et al. [3] concluded that a substantial proportion of spatters within the Al-Si10-Mg material fell within the diameter range of 100 μm to 200 μm . As a result, spatter sizes of 100 μm , 150 μm , and 200 μm were specifically chosen for detailed investigation. Furumoto et al. [4], in their research, determined that

the ejection angles of spatters typically ranged from 10° to 60°. Consequently, ejection angles of 10°, 35°, and 60° were selected for the current analytical approach.

In the findings of Young et al. [11], type one, characterized by metallic jet, exhibited the highest spatter velocity among various types, measuring at 2.17 m/s, with a corresponding diameter of 33 μm .

Table 5, Table 6, and Table 7 display a matrix of nine input parameters for each velocity per spatter, considering two distinct materials: AlSi10Mg with a density of 2676 kg/m³ and stainless steel 316L with a density of 7950 kg/m³. The simulation was conducted twice for AlSi10Mg, differing in velocity (high and low), aiming to explore spatter behavior and transport on the build plate and in nearby regions. The velocity variation was based on the experimental data reported by Young et al.'s [11] for various spatter diameters of AlSi10Mg for the low velocity simulations.

The simulation was conducted twice for AlSi10Mg, differing in velocity (high and low), aiming to explore spatter behavior in regions near and above the build plate. The velocity variation was achieved by utilizing a diameter ratio, as seen in Young et al.'s [11] study, specifically for the lower velocity within AlSi10Mg.

Anwar et al. [5] presented velocities for both AlSi10Mg and SS 316L corresponding to different diameters, which were employed in the high-velocity simulations for both materials in the Discrete Phase Model (DPM) of this study.

Within the DPM simulations, three positions—right, center, and left of the build plate—were thoroughly investigated. The positions are illustrated in Figure 37. This configuration was applied to both the initial and final designs, enabling a comprehensive comparative analysis of the effects arising from the implemented chamber modifications. This comprehensive approach facilitated a detailed understanding of the impact of these alterations within the chamber setup. The boundary conditions were set trapped for the bottom wall and build plate and reflected for the rest of the walls.

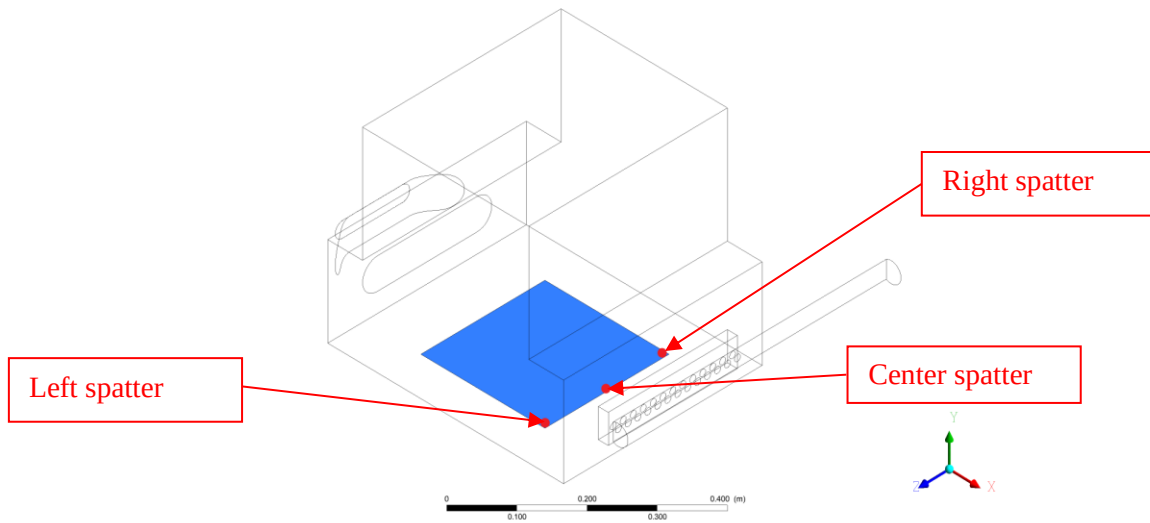


Figure 37 schematic for the spatter's positions.

100 μm		150 μm		200 μm	
Velocity m/s	Angle $^\circ$	Velocity m/s	Angle $^\circ$	Velocity m/s	Angle $^\circ$
0.68	10	0.45	10	0.34	10
	35		35		35
	60		60		60

Table 5. Spatter configurations for low velocity AlSi10Mg.

100 μm		150 μm		200 μm	
Velocity m/s	Angle $^\circ$	Velocity m/s	Angle $^\circ$	Velocity m/s	Angle $^\circ$
4.75	10	2.11	10	1.18	10
	35		35		35
	60		60		60

Table 6. Spatter configurations for high velocity SS 316L.

100 μm		150 μm		200 μm	
Velocity m/s	Angle $^\circ$	Velocity m/s	Angle $^\circ$	Velocity m/s	Angle $^\circ$
5.06	10	3.92	10	3.27	10
	35		35		35
	60		60		60

Table 7. Spatter configurations for high velocity AlSi10Mg.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Mesh Independence Study

A comprehensive analysis of six different mesh configurations was undertaken to determine the optimal mesh for the study. These configurations included mesh sizes of 10 mm, 7.5 mm, 5 mm, and 4 mm, as well as two refined variations: 5 mm with level 3 refinement in the inlet, outlet, and nozzles, and 4 mm with level 3 refinement in the same areas. To evaluate the performance of these mesh configurations, the center plane's average velocity and the chamber outlet velocity were compared across all of them. The assessment aimed to identify a mesh size that strikes a balance between computational efficiency and accuracy.

The results revealed that the average velocity in the center plane began to stabilize when the mesh element count reached 3 million. This observation is illustrated in Figure 42, highlighting that the 5 mm mesh element size was sufficient to provide reliable results.

However, when scrutinizing the discharge of the 5 mm mesh as shown in Figure 38, it became evident that the boundary layer near the wall was relatively thick. Consequently, additional refinement in specific areas was considered. This refinement led to a substantial reduction in the boundary layer, as depicted in Figure 40. In this refined mesh configuration, the velocity near the wall approached nearly zero due to the no – slip boundary condition at the walls.

Comparing the 5 mm refined mesh with the 4 mm refined mesh, it was observed that the difference is minimal as illustrated Figure 43. The velocity profile is almost identical between the 4mm refined mesh and 5mm refined mesh, despite the significantly larger number of elements in the 4 mm refined mesh. Consequently, the 5 mm refined mesh was selected as the most suitable option for the study, offering a balance between computational efficiency and accurate results. All the meshes have the same boundary

conditions with 5 m/s for the inlet argon flow. The model used in this study is k- ϵ realizable model for all simulations.

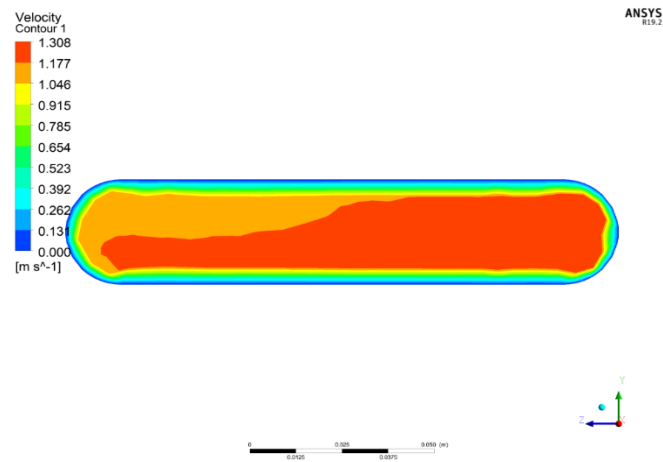


Figure 38. Velocity contours at outlet for 5 mm mesh size.

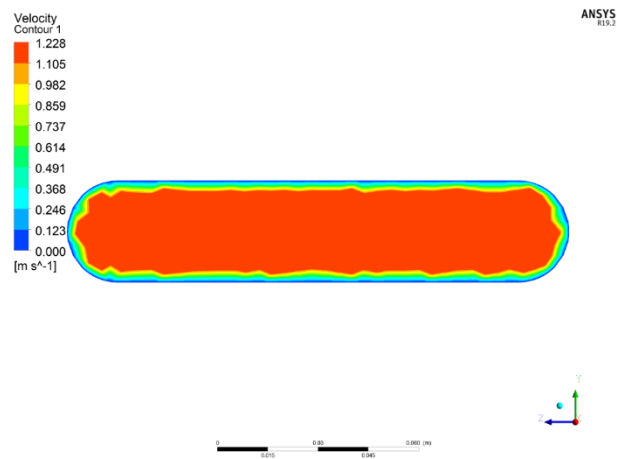


Figure 39. Velocity contours at outlet for 4 mm mesh size discharge.

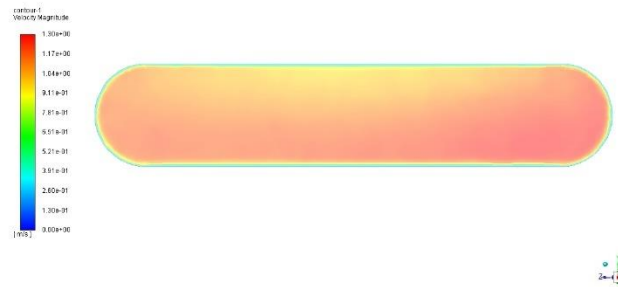


Figure 40. Velocity contours at outlet for 5 mm refined mesh size discharge.

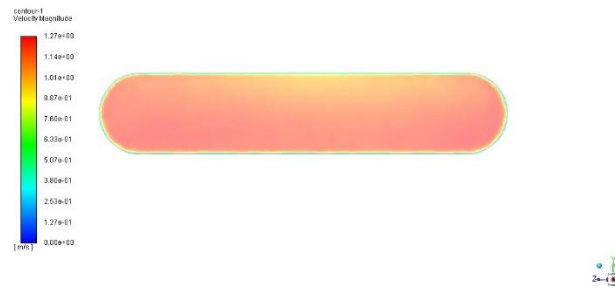


Figure 41. Velocity contours at outlet for 4 mm refined mesh size discharge.

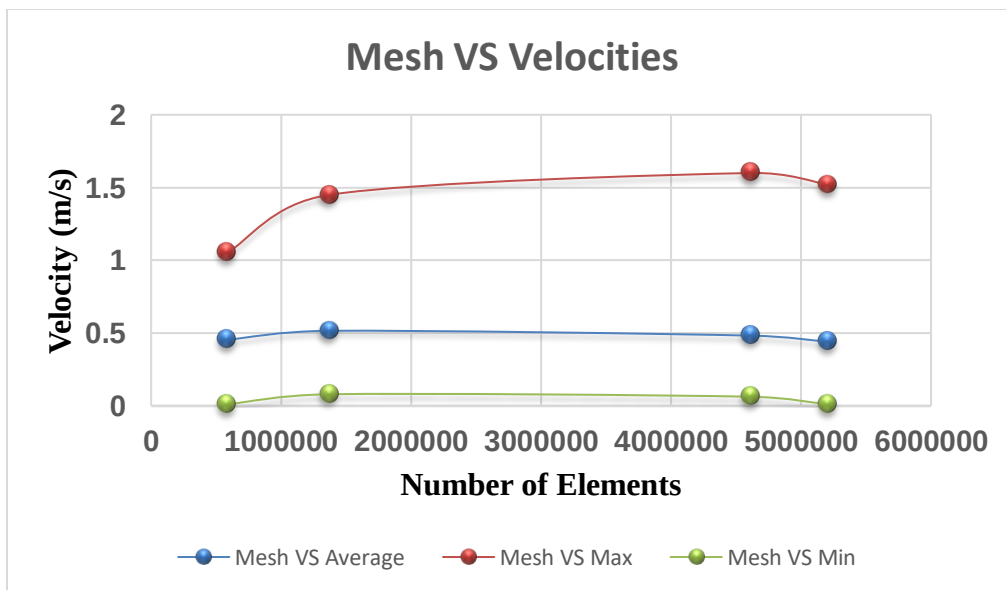


Figure 42. XY center plane velocities for different meshes.

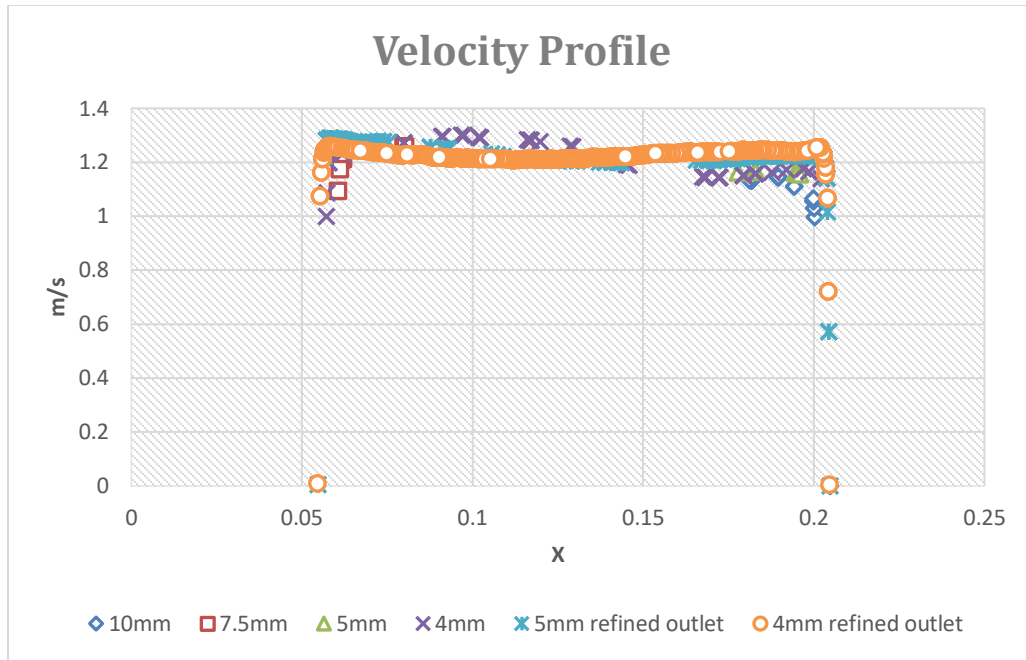


Figure 43. Velocity profiles in the discharge for different meshes.

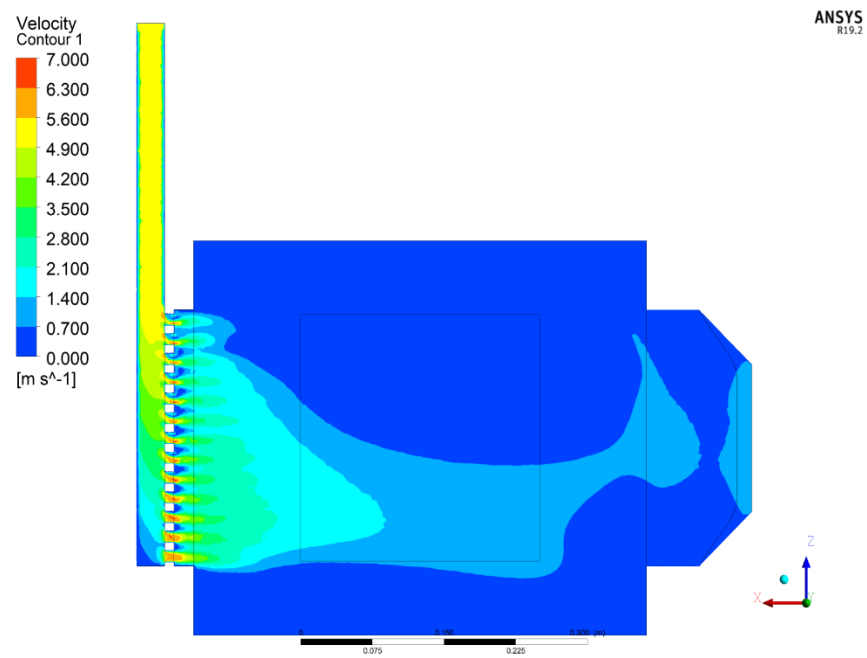


Figure 44. Base model XY center plane.

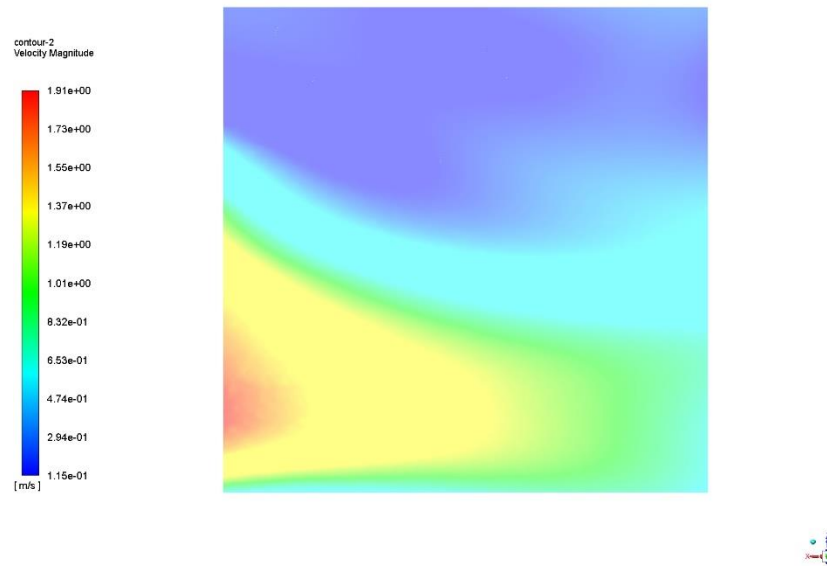


Figure 45. Base model XY bounded center plane.

4.2 Argon Flow Results

4.2.1 Varying nozzle length

The modification involving variations in nozzle length successfully shifted the flow profile, and the key parameter influencing the profile is the variation between the nozzle lengths. It was observed that the greater the variation between the nozzle lengths, the more the flow tends to shift towards the left side of the chamber. Among the variations tested, a 2.5 mm difference between the first nozzles and the next one had the most significant effect on the location of the flow profile, while a 2 mm variation had the least impact on the flow profile. This information is illustrated in Figure 46, Figure 47, Figure 48.

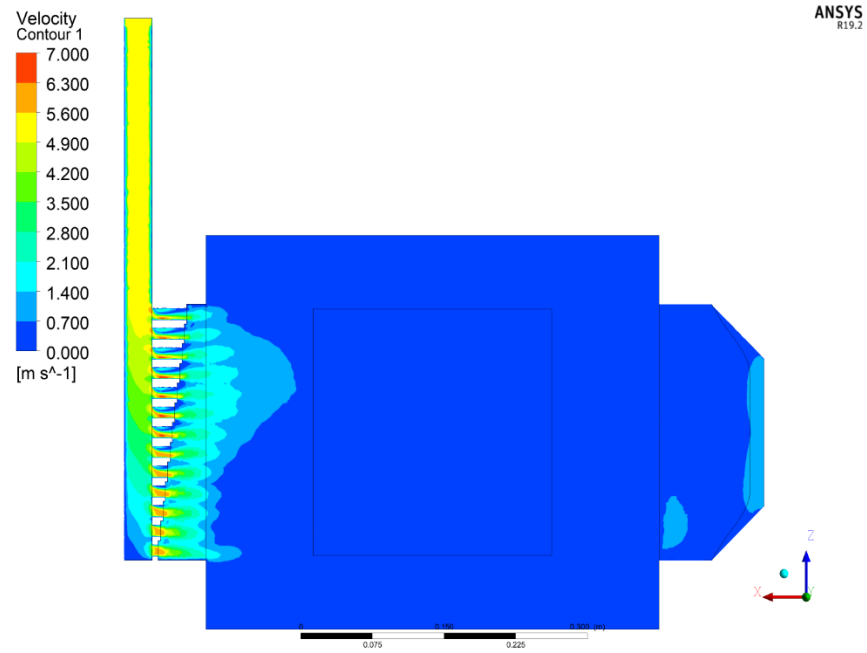


Figure 46. Nozzle with varying length, length difference is 2.5mm.

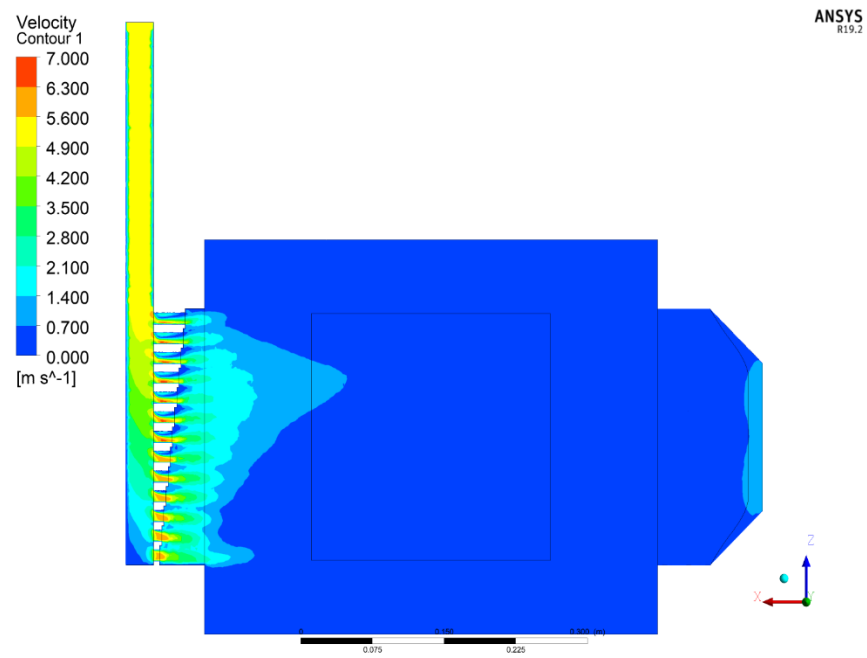


Figure 47. Nozzle with varying length, length difference is 2.25mm.

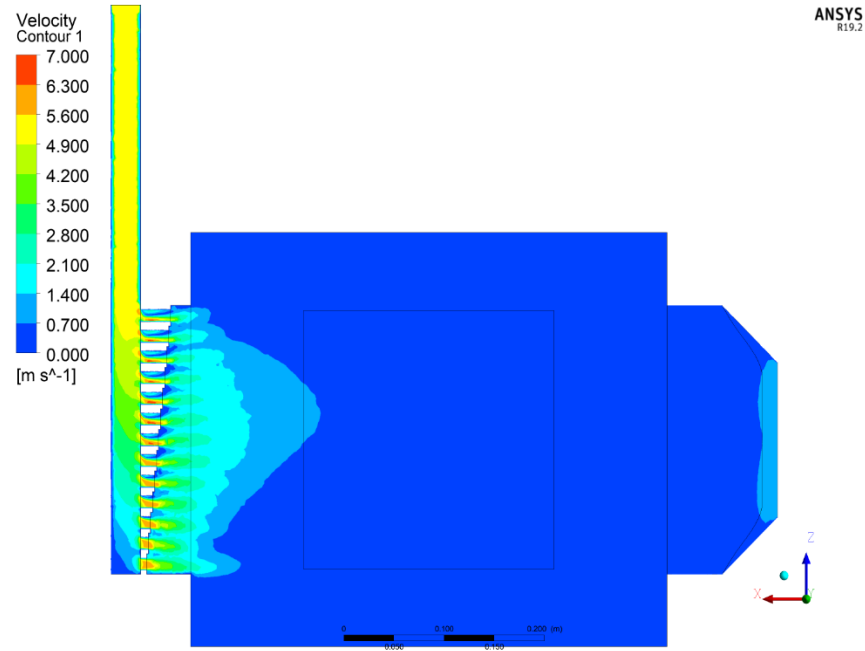


Figure 48. Nozzle with varying length, length difference is 2mm.

4.2.2 Varying discharge cross sectional areas of the nozzles

10mm, 11mm and 11.5 mm were tested for the first nozzle. The 10mm and 11 mm moved the flow to the extreme left while 11.5 mm shifted the flow slightly to the left. This could be a result of the pressure variation in the discharges of the 13 nozzles where the last nozzle discharge pressure is the highest. Figure 49, Figure 50 and Figure 51 shows the velocity profile for 10mm, 11mm and 11.5mm discharge diameter.

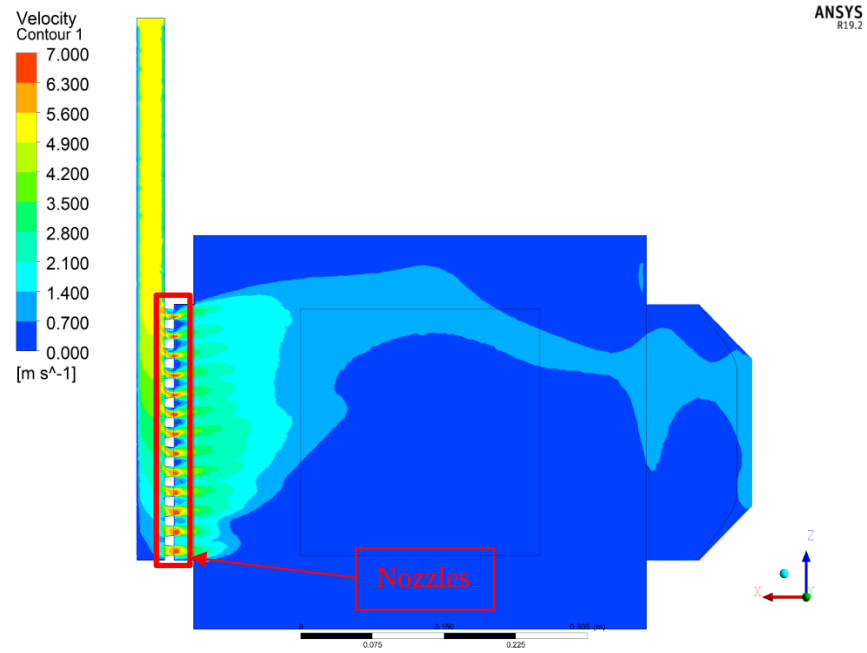


Figure 49. Varying discharge cross sectional areas, 10mm discharge diameter.

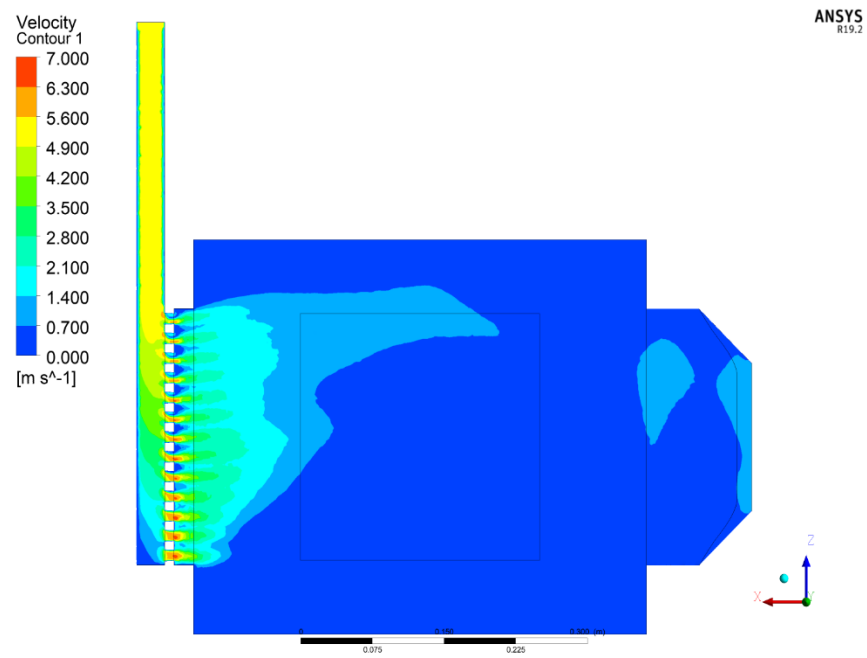


Figure 50. Varying discharge cross sectional areas, 11mm discharge diameter.

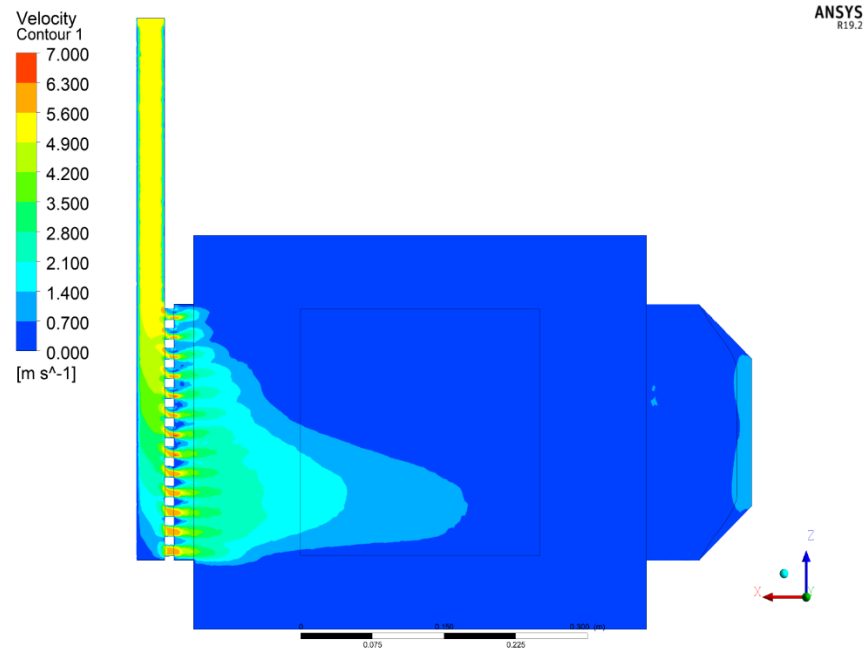


Figure 51. Varying discharge cross sectional areas, 11.5mm discharge diameter.

4.2.3 Incline Angle

The incline effectively enhanced the flow in the lower region, as shown in Figure 53, Figure 54, and Figure 55. However, the difference between the three angles is not substantial. The enhancement is due to eliminating the corner after admitting the argon since corners and sudden changes like step change can disturb the flow and create vortices which is unfavorable.

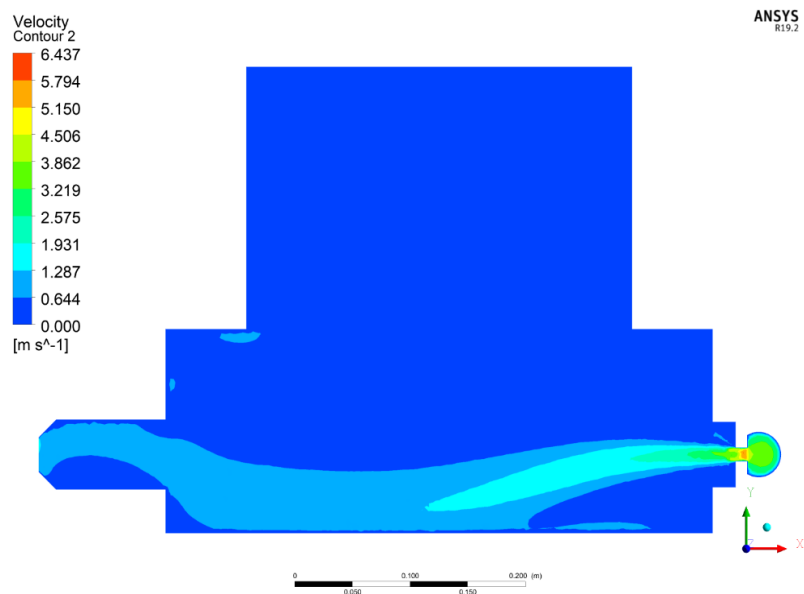


Figure 52. Base model XY plane at the center

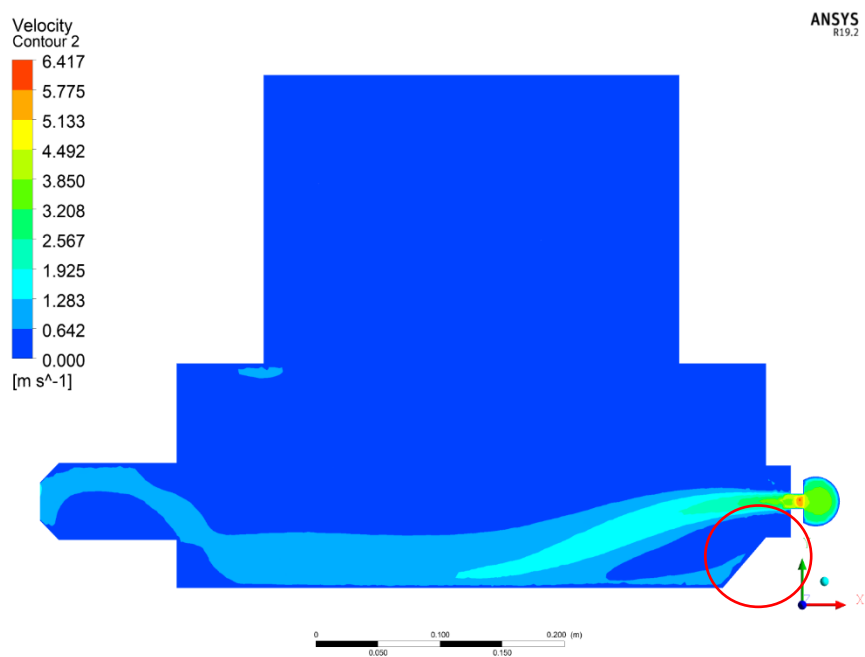


Figure 53. Incline with 41.53° angle, XY plane at the center.

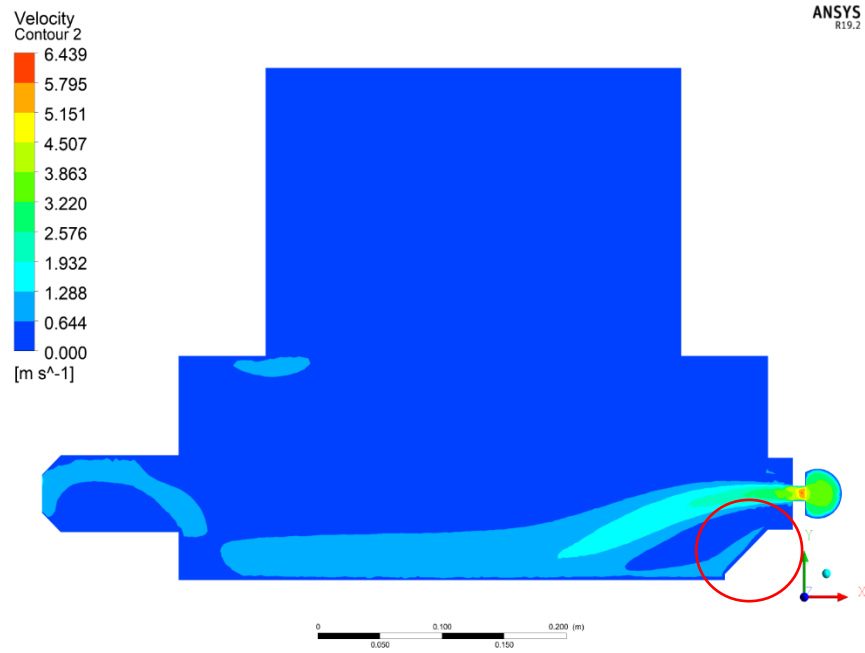


Figure 54. Incline with 45° angle, XY plane at the center.

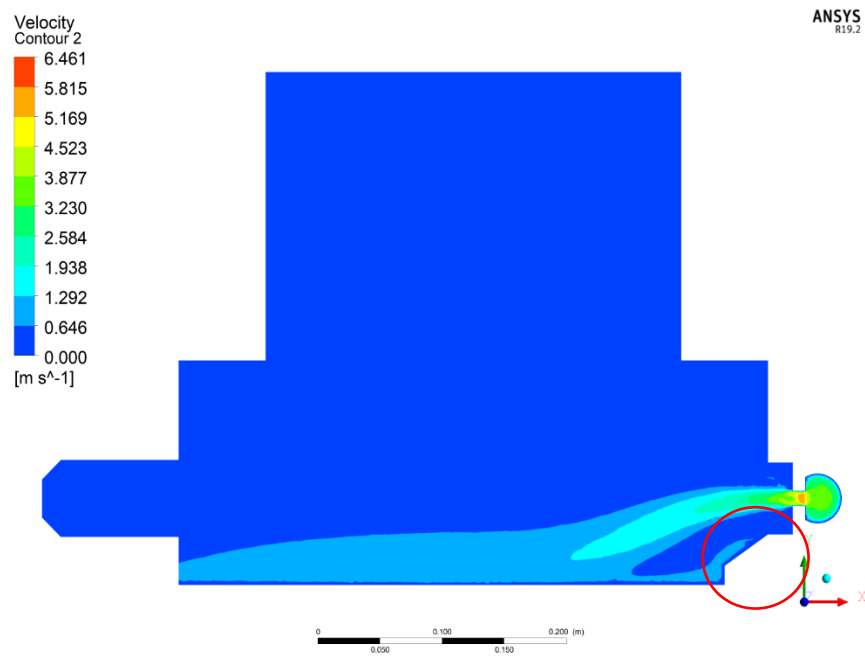


Figure 55. Incline with 55° angle, XY plane at the center.

4.2.4 Fillet

The introduction of fillets has successfully reduced flow separation within the nozzles, which is a positive outcome for improving flow dynamics. However, it appears that the fillets also have an effect on shifting the flow profile to the right and introducing skewness to the flow. The extent of this shift and skewness is influenced by the radius of the fillet. Here are some key observations regarding the fillet modifications:

1. One-Side Fillet: In this modification, different radii were selected, such as 0.5 mm, 1.5 mm, and 2 mm. The results indicate that as the radius increases, the flow profile is more skewed to the right. For example, comparing Figure 57 and Figure 58, the 2 mm radius introduces more skewness than the 1.5 mm radius.
2. Two-Side Fillet: This modification also had varying radii, such as 0.25 mm and 0.5 mm. The two-side fillet had a more significant impact on shifting the flow profile to the right compared to the one-side fillet. Figure 56 (one-side fillet with a 0.5 mm radius) and Figure 60 (two-side fillet with a 0.5 mm radius) show that the two-side fillet introduced more skewness in the flow profile.

These findings indicate that the radius of the fillet plays a crucial role in determining the degree of shift and skewness in the flow profile. Engineers and designers must carefully consider the radius value when implementing fillets to optimize flow characteristics while minimizing any undesired effects on the flow

profile. The goal is to achieve a balance between reduced separation and maintaining a more centered and uniform flow profile.

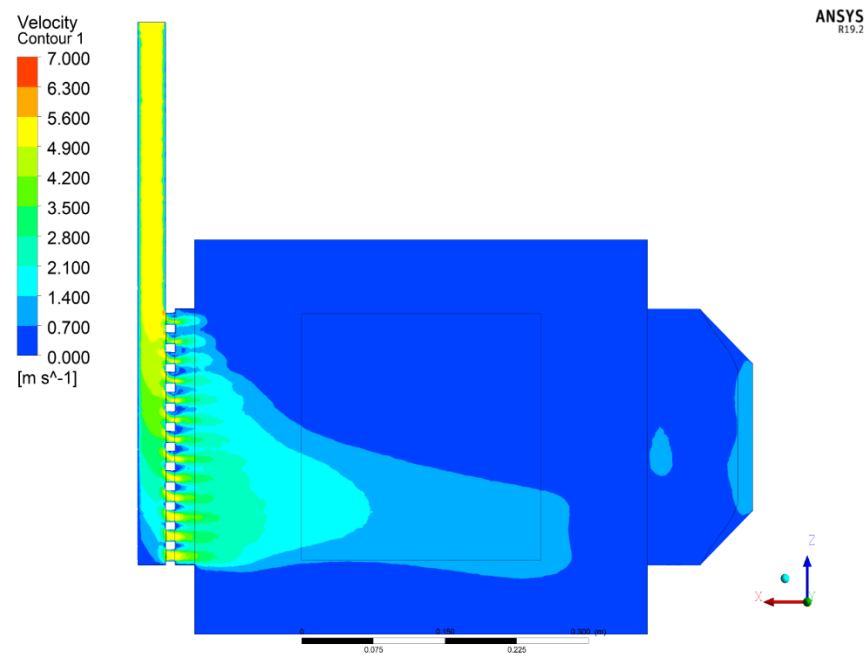


Figure 56. 0.5mm radius fillet on one side.

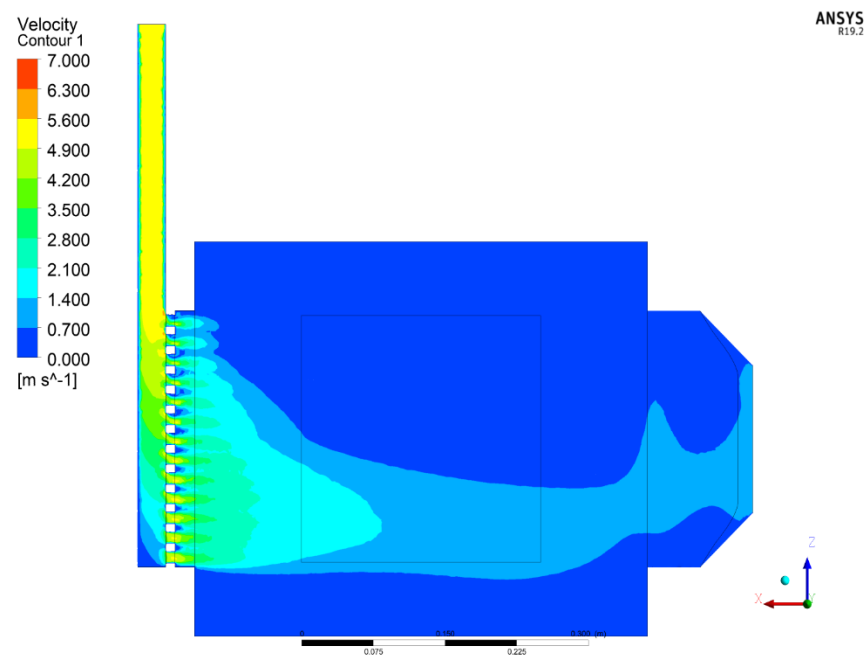


Figure 57. 1.5mm radius fillet on one side.

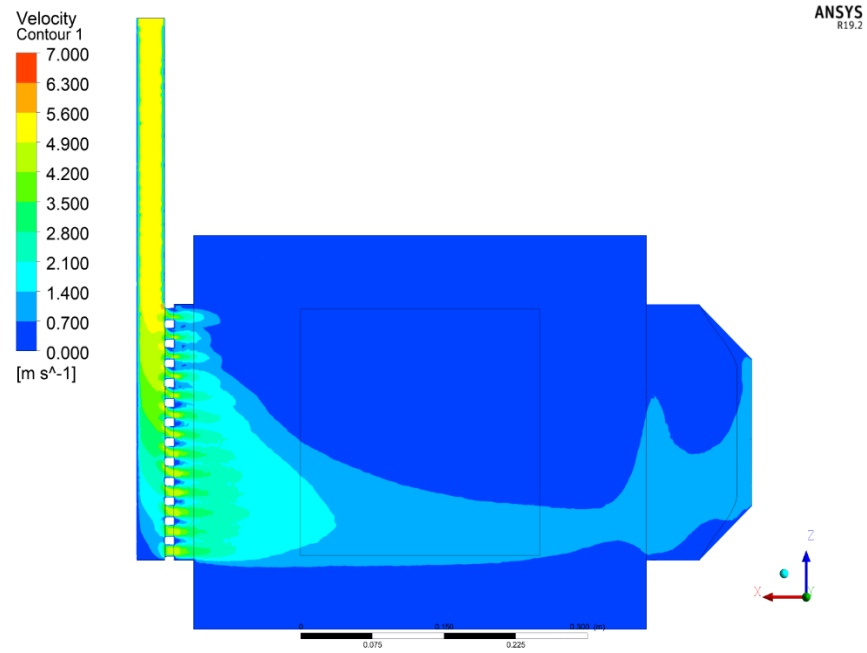


Figure 58. 2mm radius fillet on one side.

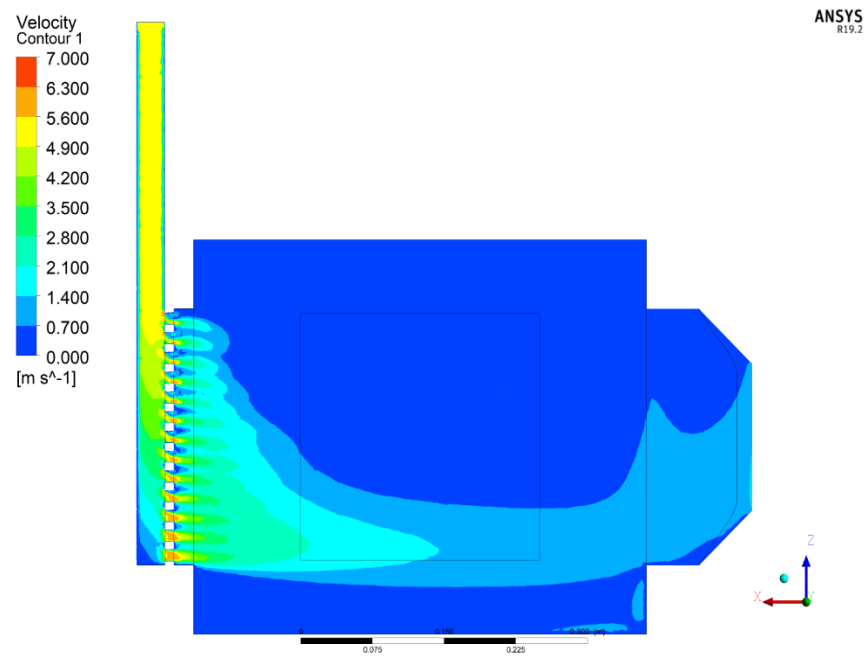


Figure 59. 0.25mm radius fillet on two sides.

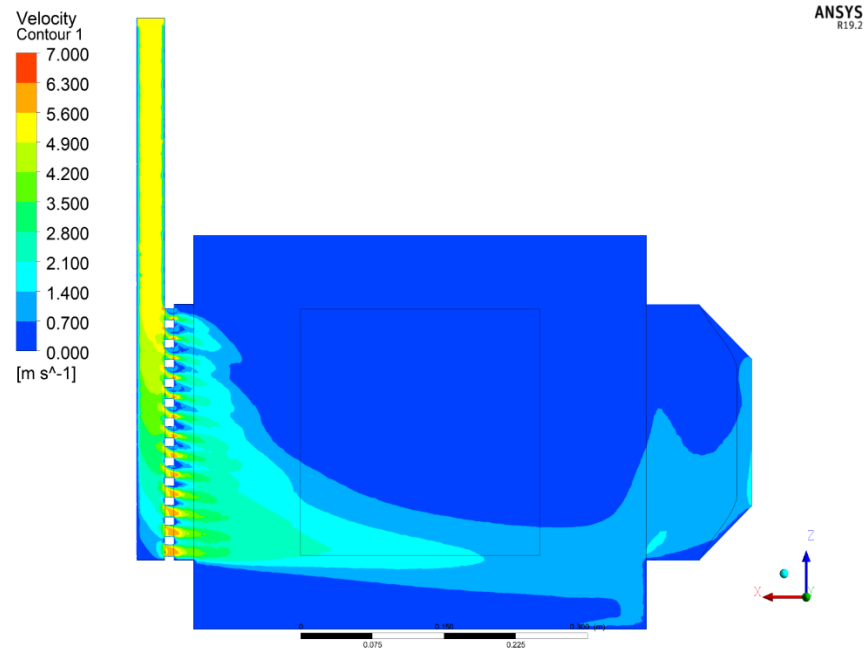


Figure 60. 0.5 mm radius fillet on two sides.

4.2.5 Inlet header

The result of this modification was a noticeably more symmetrical shape and a repositioned, centered flow profile within the chamber. This adjustment shows promise in rectifying the observed asymmetry and improving the overall balance of flow dynamics. A comprehensive examination is recommended to thoroughly evaluate the implications of this symmetrical inlet configuration on the flow behavior within the chamber.

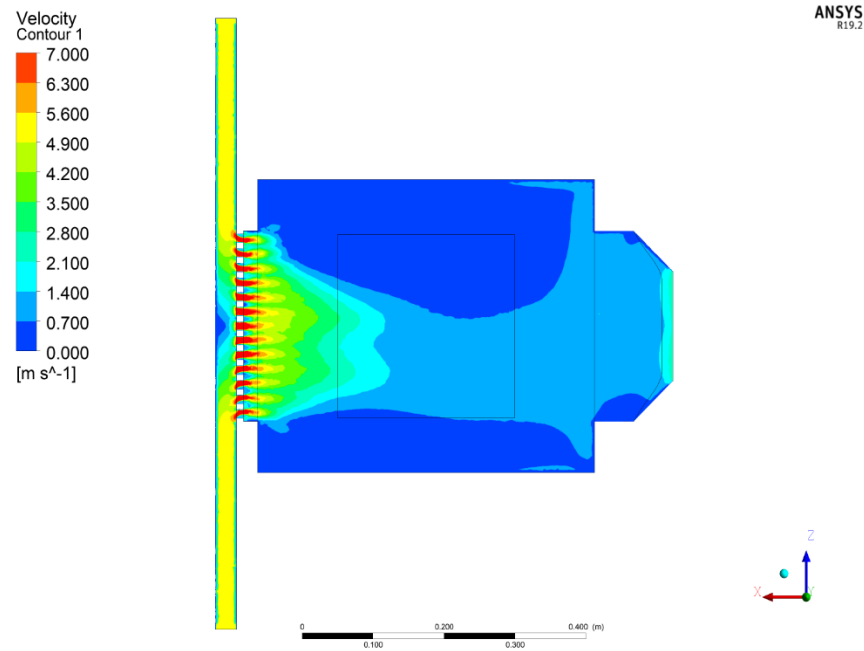


Figure 61. Base model with two inlet headers.

4.2.6 Final design

Notably, both Design 3 and Design 4 exhibited superior flow uniformity, as evident in Figure 64 and Figure 65. In terms of the high-velocity region within the flow profile, Design 3 and Design 4 exhibited more square profiles compared to Design 1, Design 2, and the base model. Design 1 and Design 2 outperformed the base model with regard to the high-velocity region. However, Design 1 displayed a somewhat right-skewed profile, while Design 2 exhibited a milder skewness to the left, albeit with some flow disturbances. The most remarkable results in terms of uniformity were observed in Design 3 and Design 4. Nevertheless, it's worth noting that Design 3 displayed increased skewness to the left in the lower-velocity region, indicating a trade-off between overall uniformity and the specific flow characteristics in this region.

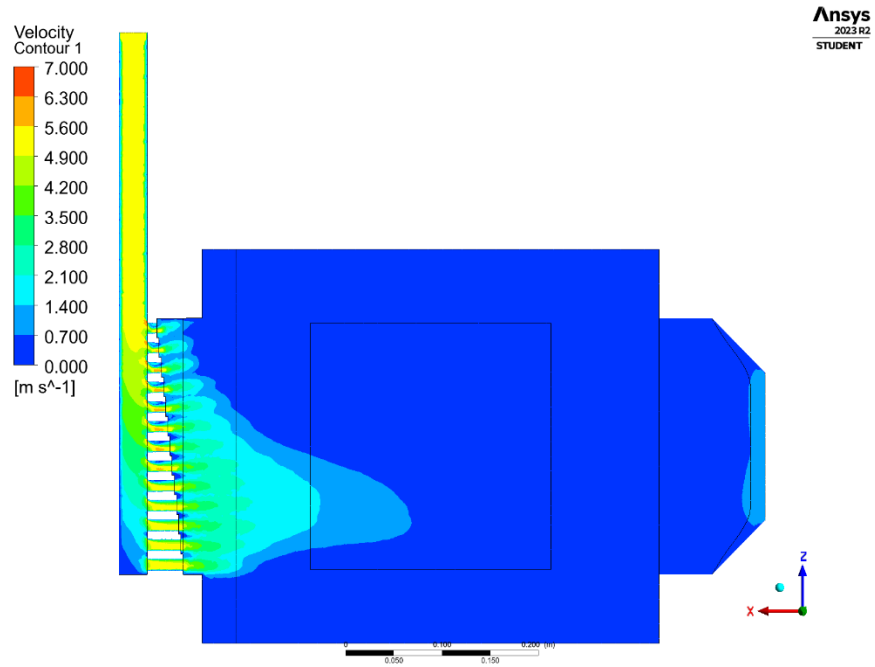


Figure 62. Design 1.

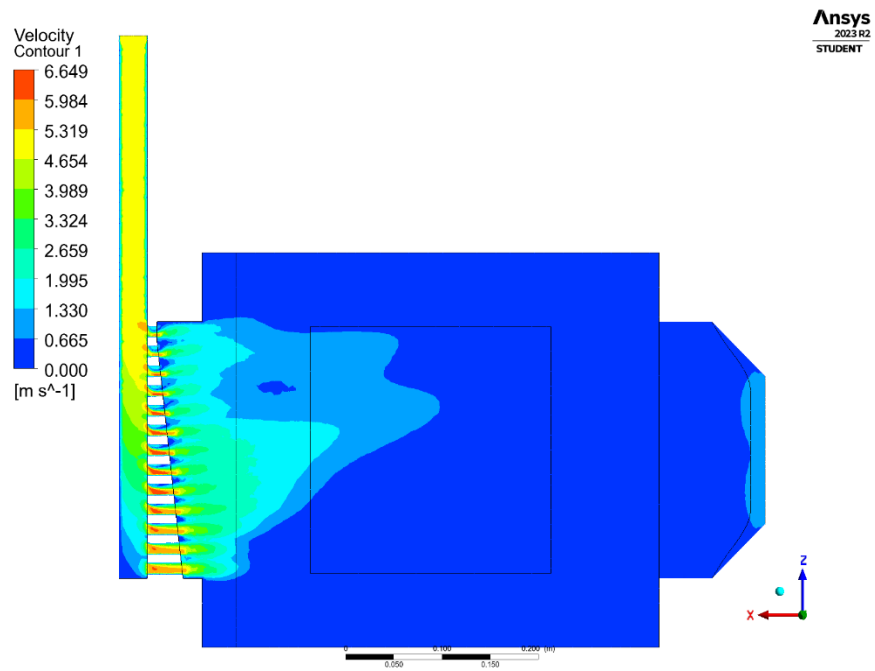


Figure 63. Design 2.

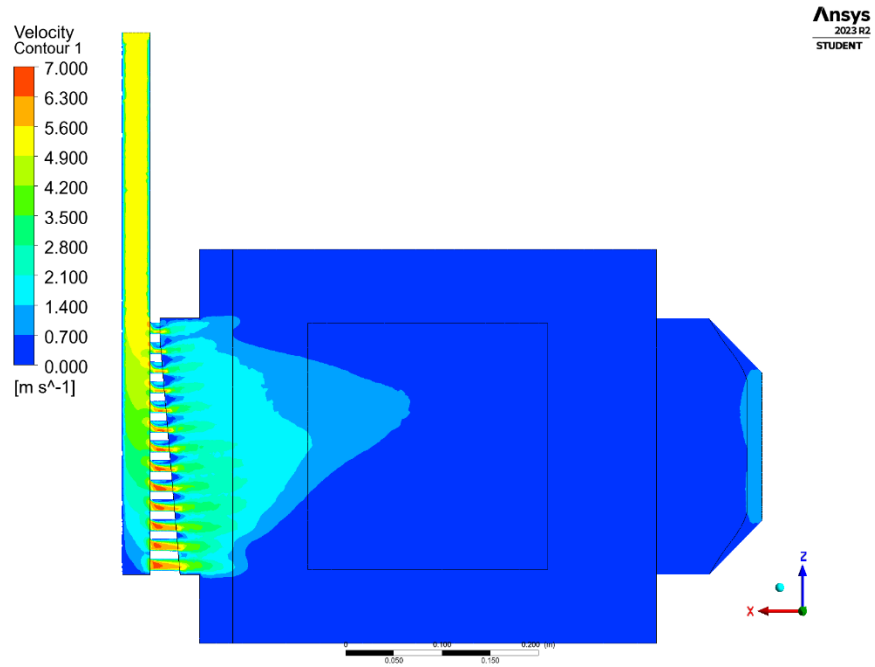


Figure 64. Design 3.

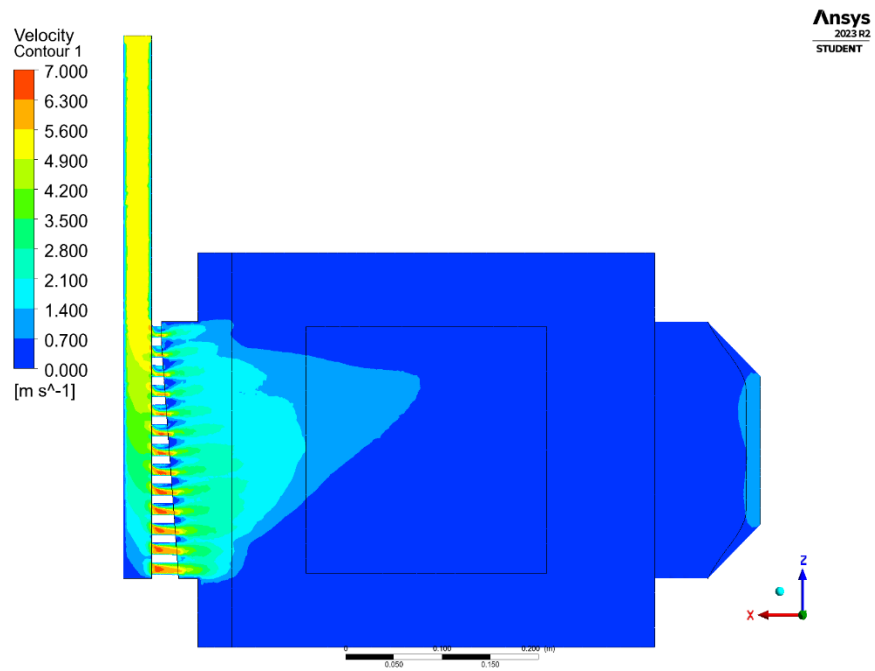


Figure 65. Design 4.

4.3 DPM Results and Discussion

As illustrated in Section 3.3 Geometrical Changes, 2 different inlet boundary condition were utilized to confirm the performance of the final design. In this section, the results from both inlet conditions were investigated with DPM. The inlet conditions are 5 m/s and 10 m/s where the inlet velocity of 5 m/s corresponds to volume flow rate of 250 liters per minute (LPM).

4.3.1 Base Volume Flow Rate (250 LPM)

1. Low Velocity AlSi10Mg

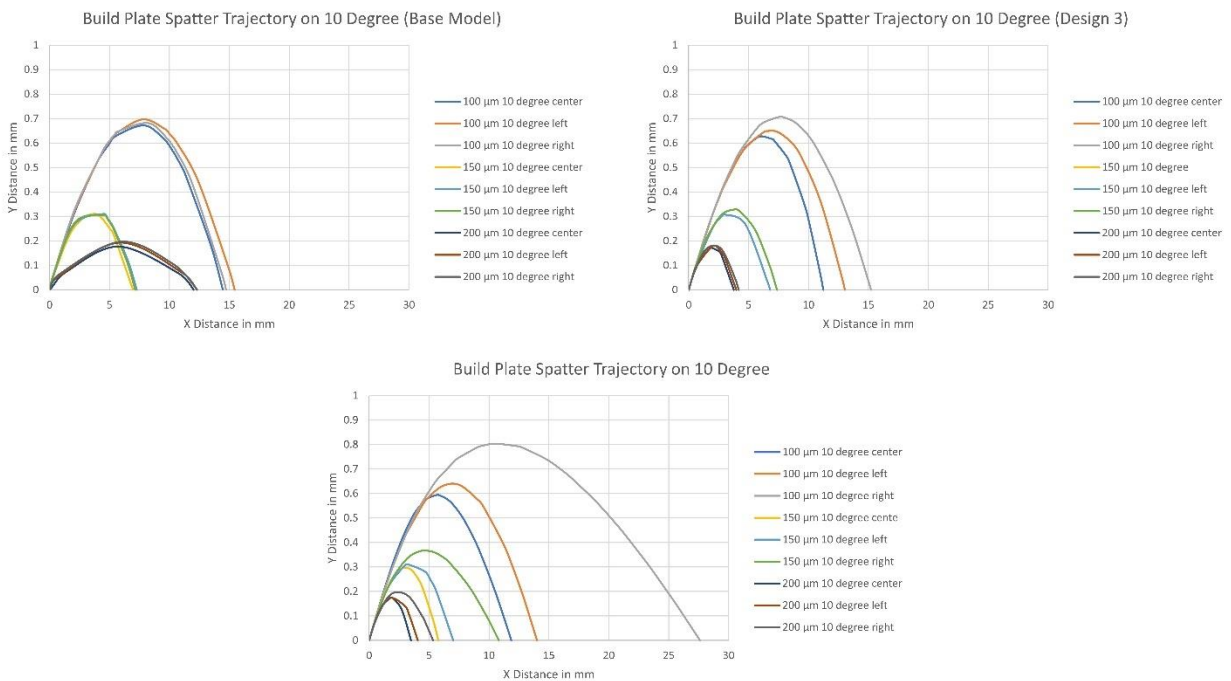


Figure 66. Comparison between base model, design 3 and design 4 for 10 ° ejection angle.

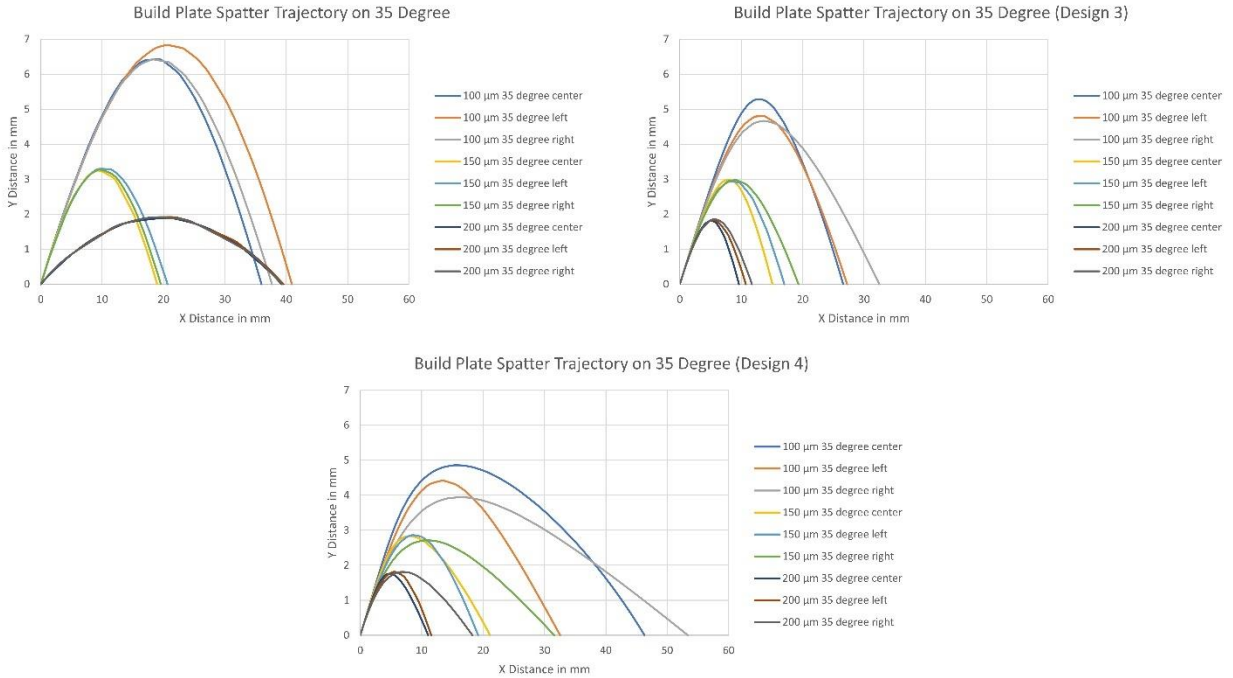


Figure 67. Comparison between base model, design 3 and design 4 for 35 ° ejection angle.

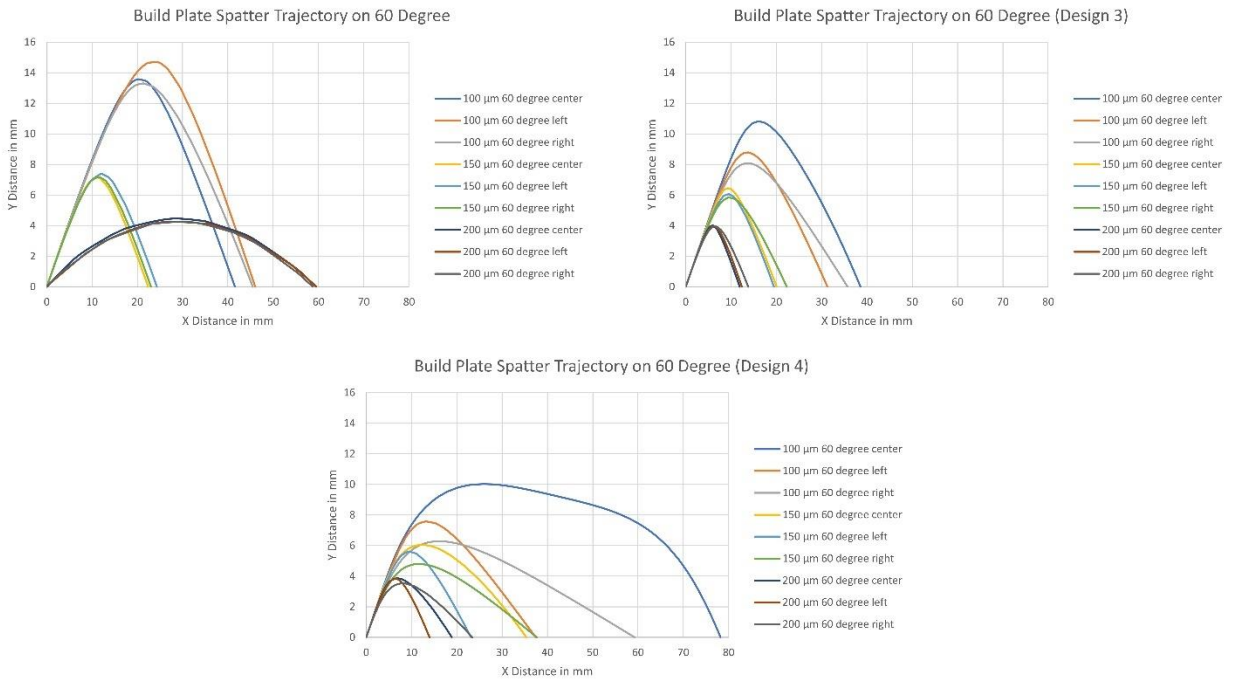


Figure 68. Comparison between base model, design 3 and design 4 for 60 ° ejection angle.

In the simulation of low-speed AlSi10Mg processing, focusing specifically on central spatter, the Discrete Phase Model (DPM) analysis indicates the superior efficacy of the base model in spatter elimination across

varying particle sizes. Notably, for 100 μm spatter, the standard deviation of results for design 3 is recorded as 10.2, while the base model and design 4 exhibit standard deviations of 13.6 and 21.6, respectively. Similar trends persist for spatter sizes of 150 μm and 200 μm , wherein design 3 consistently outperforms both design 4 and the base model, as elucidated in Table 8. Calculating the average of the standards deviation is shown in Table 9, clearly design 3 surpasses base model with standard deviation average of 6.9 while for base model, it is 13.8.

Spatter size	100 microns				150 microns				200 microns			
Model	Min.	Max.	Mean	STD	Min.	Max.	Mean	STD	Min.	Max.	Mean	STD
Base model	14.5	46.0	32.5	13.6	7.0	24.3	16.7	7.4	12.0	59.5	36.9	20.4
Design 3	11.2	38.6	25.7	10.2	6.2	22.3	14.9	6.4	3.8	13.8	9.1	4.0
Design 4	11.9	78.2	40.1	21.6	5.8	37.6	21.3	11.9	3.5	23.4	12.2	7.1

Table 8. Minimum and maximum spatter travelling distance, mean distance, and standard deviation for low speed AlSi10Mg.

Spatter size	100 microns	150 microns	200 microns	Average STD	STD Average Change
Base model	13.6	7.4	20.4	13.8	-
Design3	10.2	6.4	4.0	6.9	50%
Design 4	21.6	11.9	7.1	13.5	2%

Table 9. Average standard deviation and change in percent with respect to the base model for low speed AlSi10Mg.

2. High Velocity AlSi10Mg

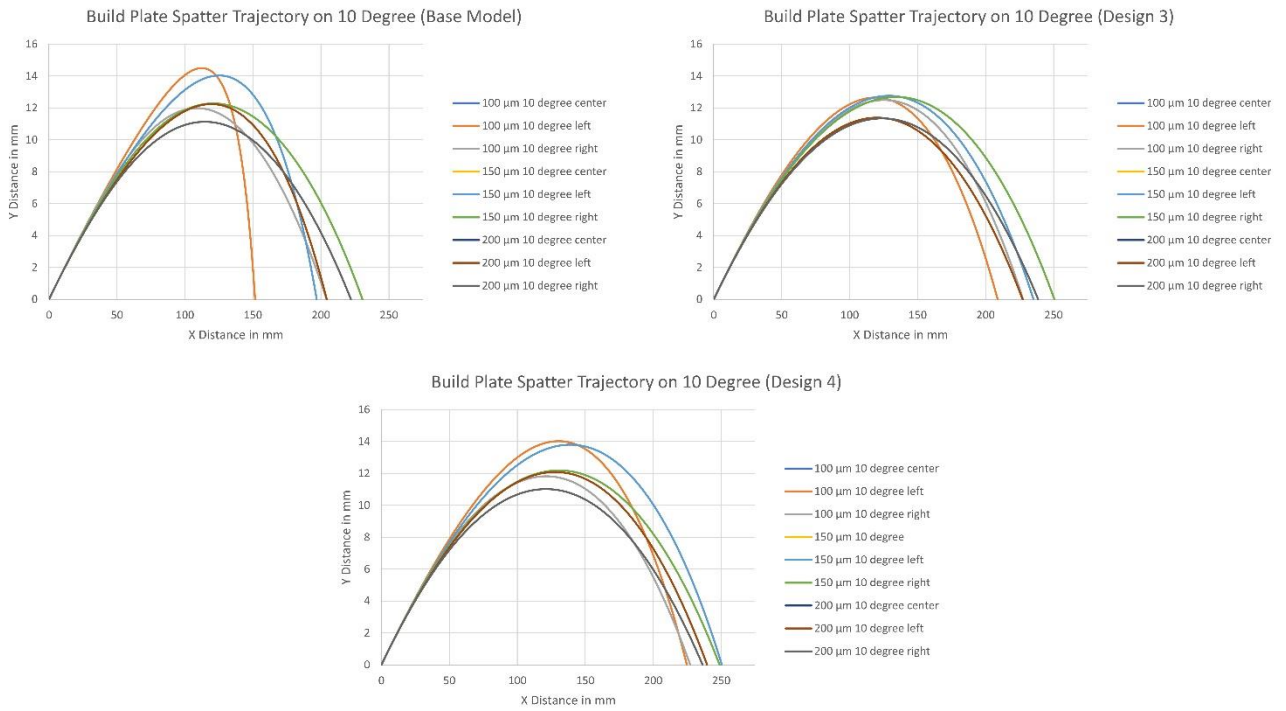


Figure 69. Comparison between base model, design 3 and design 4 for 10 ° ejection angle.

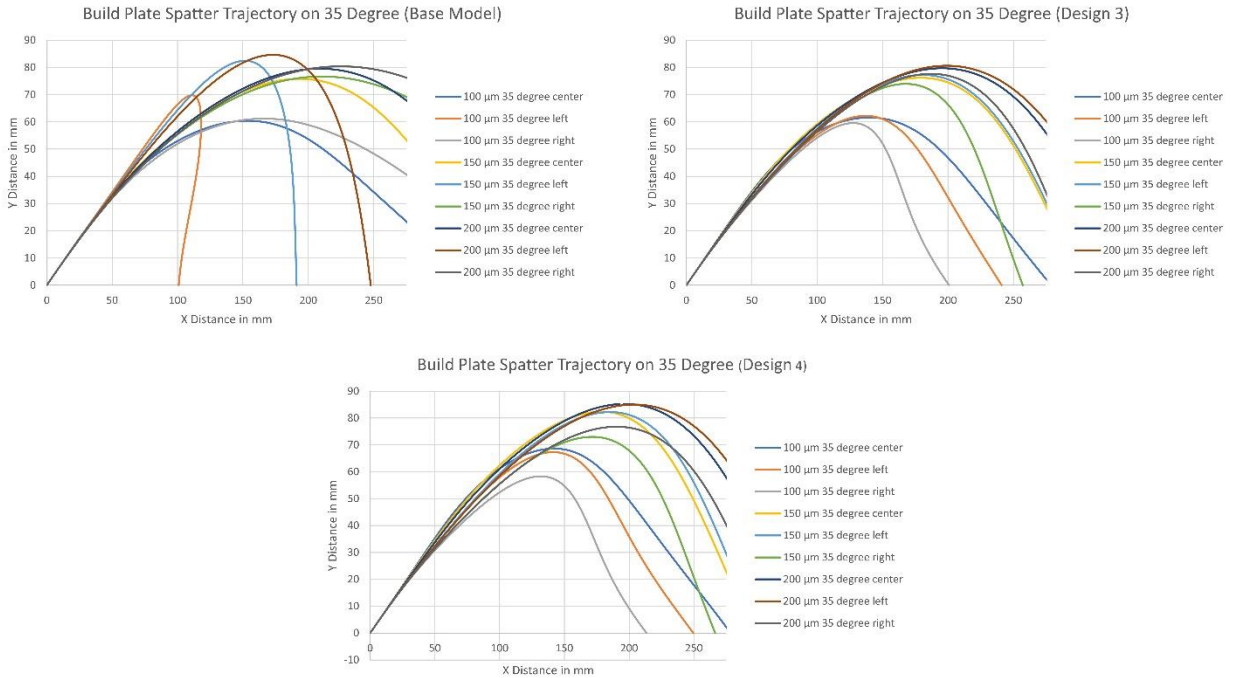


Figure 70. Comparison between base model, design 3 and design 4 for 35 ° ejection angle.

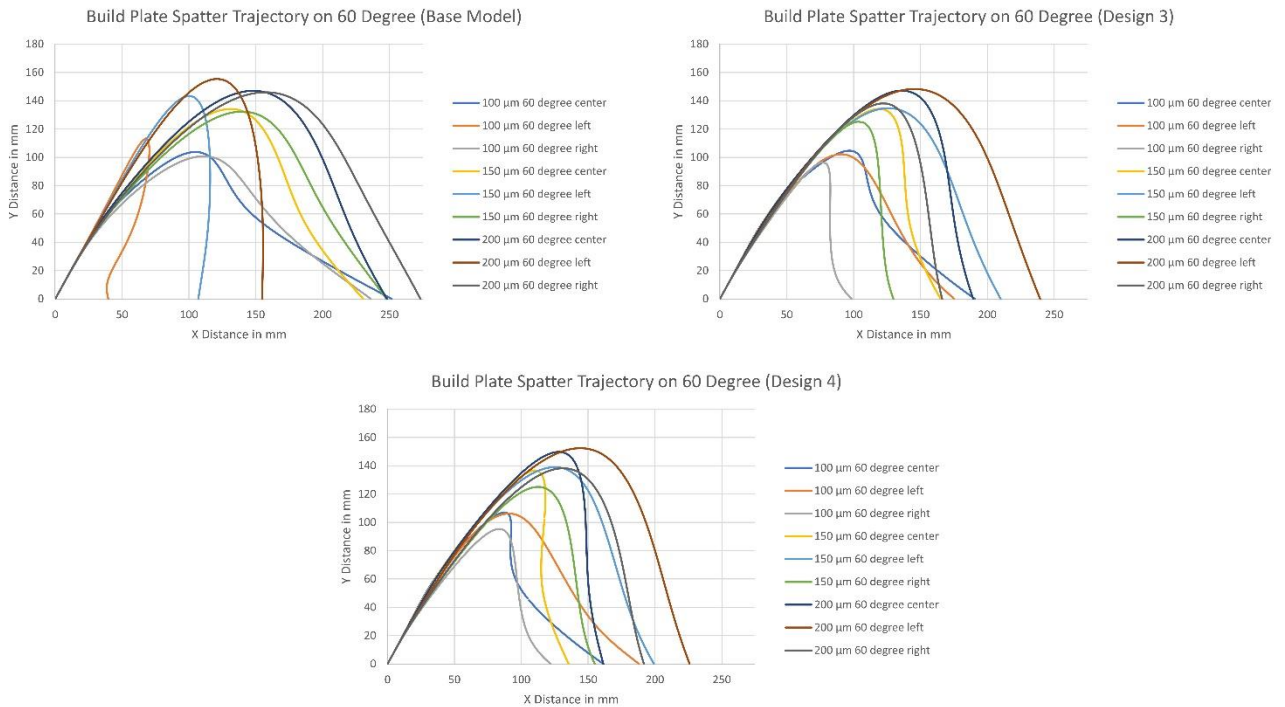


Figure 71. Comparison between base model, design 3 and design 4 for 60 ° ejection angle.

In the high-speed AlSi10Mg simulation, the center spatter in all three designs reveals that three spatters were ejected from the build plate, specifically the 100 μ m, 150 μ m, and 200 μ m spatters at a 35° angle. However, for the 10° spatter, design 4 displays the most favorable outcomes, even though all spatters landed on the build plate. In design 4, the DPM data for the 150 μ m spatter at a 10° angle indicates a travel distance of up to 239mm, as opposed to 226.46mm in the base model, marking a 5% increase in travel distance. Similarly, the 100 μ m spatter at a 10° angle traveled 197mm in the base model, while in design 4, it traveled 210mm, reflecting a 6% increase in distance.

Design 3 displays significant variation in the removal of the 100 μ m and 150 μ m spatters at a 10° angle. However, it performs worse in removing the 200 μ m spatter at a 10° angle. Notably, all spatters at a 60° angle fall onto the build plate, with designs 3 and 4 exhibiting less favorable outcomes.

In the left plane, design 4 outperforms the base model by removing four spatters. Interestingly, all spatters at 65° land outside the build plate, while in the base design, these same spatters land on the plate. Moreover, the 150 μ m spatter at a 10° angle lands outside the build plate, whereas the 200 μ m and 100 μ m spatters land at the end of the build plate. Design 3 shows results between design 4 and the base model.

In the right plane, the base design removes four spatters, three of them at a 35° angle, while the fourth is a 200 μ m spatter ejected at a 35° angle. In contrast, designs 3 and 4 remove the 100 μ m and 200 μ m spatters at a 35° angle. All spatters at a 10° angle traveled a distance greater than 225mm in designs 3 and 4, while in the base build, they traveled less than 225mm but more than 200mm. However, all the 65° spatters traveled less than 200mm in design 4 and less than 175mm in design 3, whereas in the base model, these same spatters traveled more than 200mm, with one of them falling outside the build plate. Furthermore, in design 4, the standard deviation registers the lowest value, or a negligible difference when compared to both the base model and design 3. This observation suggests a more uniform flow, even though not all spatters were successfully removed from the build plate. Specifically, for 100 μ m spatter, design 4 records a standard deviation of 46.5, while for 150 μ m and 200 μ m spatters, the values are 57.9 μ m and 62,

respectively, as presented in Table 10. Moreover, design 4 shows the lowest standard deviation recorded 30% less than the base model as illustrated in Table 11.

Spatter size	100 microns				150 microns				200 microns			
Model	Min.	Max.	Mean	STD	Min.	Max.	Mean	STD	Min.	Max.	Mean	STD
Base model	70.4	341.6	211.0	90.3	115.9	362.1	239.3	77.1	155.5	362.3	254.9	69.2
Design 3	98.5	279.2	200.1	50.3	129.7	302.9	229.5	57.8	166.2	342.4	249.8	62.8
Design 4	122.0	278.3	208.4	46.5	135.5	299.9	232.2	57.9	161.4	340.1	251.9	62.0

Table 10. Minimum and maximum spatter travelling distance, mean distance, and standard deviation for high speed AlSi10Mg.

Spatter size	100 microns	150 microns	200 microns	Average STD	STD Average Change
Base model	90.3	77.1	69.2	78.8	-
2 inlets	50.3	57.8	62.8	57.0	28%
Design 4	46.5	57.9	62.0	55.5	30%

Table 11. Average standard deviation and change in percent with respect to the base model for high speed AlSi10Mg.

3. High Velocity SS 316L

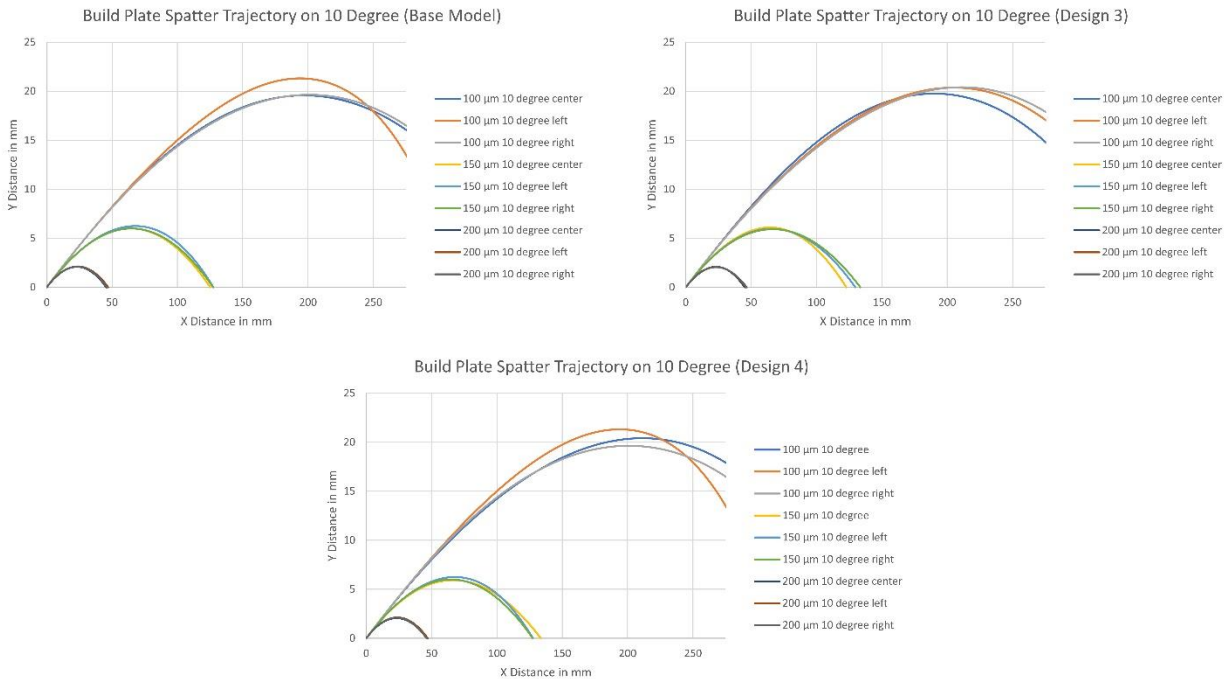


Figure 72. Comparison between base model, design 3 and design 4 for 10° ejection angle.

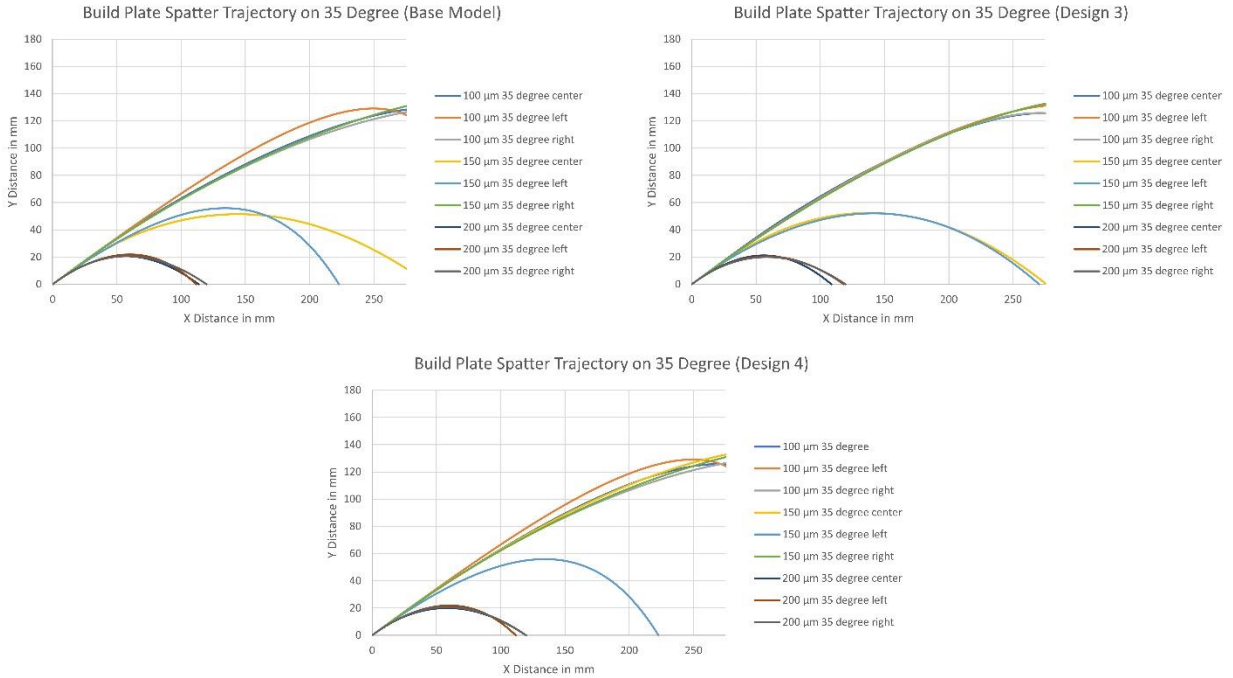


Figure 73. Comparison between base model, design 3 and design 4 for 35° ejection angle.

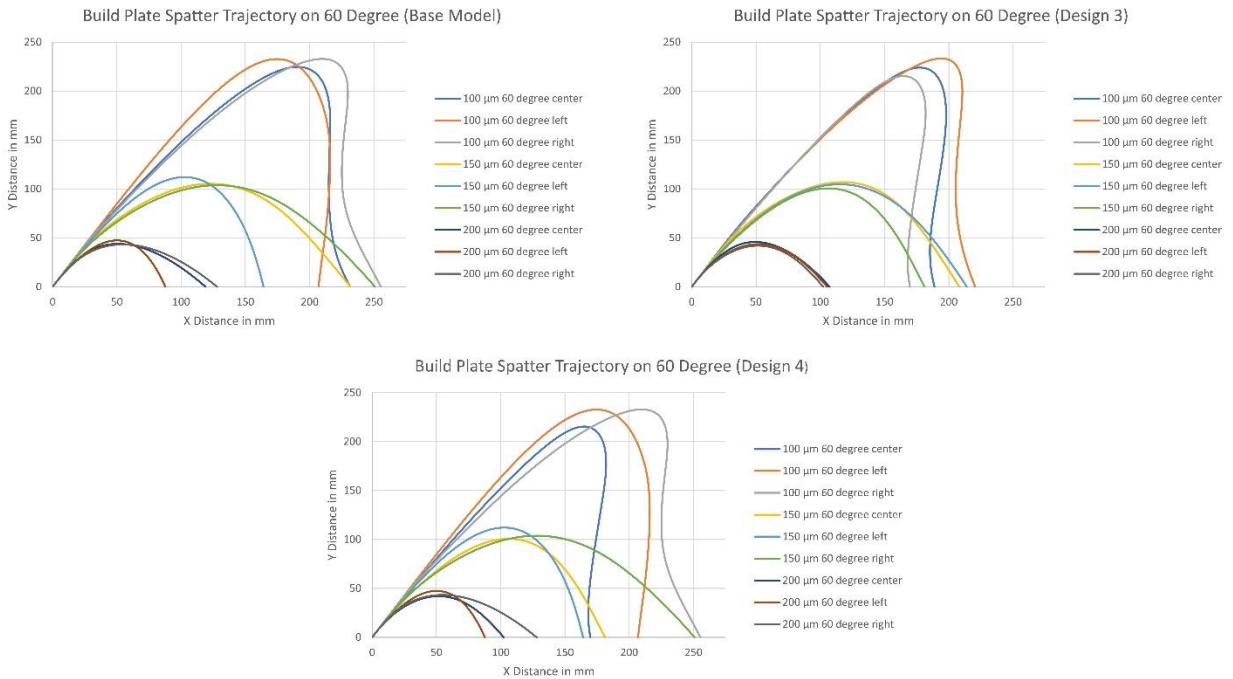


Figure 74. Comparison between base model, design 3 and design 4 for 60° ejection angle.

For the low-speed AlSi10Mg simulation within the center spatter, the DPM analysis suggests that the base model excels in spatter removal across all spatter sizes. However, when comparing right and left spatters,

design 3 appears the least efficient in spatter removal, while design 4 shows the most efficiency. For instance, considering the 100µm spatter with a 60-° ejection angle, in design 4, the spatter travels 44.62mm, compared to 26.9mm in the base model and 23.91mm in design 3, which displays the poorest performance in this scenario.

In the left spatter, both designs 3 and 4 successfully removed one more spatter, particularly the 150µm spatter at a 35° angle, compared to the base model. Additionally, the 150µm spatter at a 60° angle traveled over 215mm in designs 3 and 4, while it traveled less than 175mm in the base model. Similarly, the 200µm spatter at a 60° angle traveled over 100mm in designs 3 and 4, whereas it was less than 90mm in the base model. Surprisingly, design 3 propelled the 100µm spatter at a 60-° angle more than 220mm, performing best for this spatter, while the base model and design 4 traveled 210mm and 190mm respectively, with design 4 showing the poorest performance.

For the right spatter, the base model removed 5 spatters from the build plate, while designs 3 and 4 removed 3 spatters. The 100µm and 150µm spatters at a 35° angle landed outside the build plate in all three models. However, in the base model, two more spatters, the 100µm and 150µm spatters at a 60° angle, landed outside the build plate, while in designs 3 and 4, they landed between 150mm and 200mm. Additionally, the 200µm spatter at a 60° angle traveled up to 125mm in the base model, while in designs 3 and 4, it traveled 110mm. However, the standard deviation for base model excels design 3 and 4 recording 60.1 for 100µm, 83 for 150µm and slightly more than design 3 and 4 with standards deviation of 35.2 for 200µm as illustrated in Table 12.

Spatter size	100 microns				150 microns				200 microns			
Model	Min.	Max.	Mean	STD	Min.	Max.	Mean	STD	Min.	Max.	Mean	STD
Base model	216.0	362.4	309.8	60.1	125.1	361.7	211.6	83.0	45.6	127.9	90.9	35.2
Design 3	182.0	383.4	308.8	74.2	127.4	361.7	211.8	89.1	46.2	127.9	89.9	34.4
Design 4	182.0	383.4	308.8	74.2	127.4	361.7	211.8	89.1	46.2	127.9	89.9	34.4

Table 12. Minimum and maximum spatter travelling distance, mean distance, and standard deviation for high speed SS316L.

Spatter size	100 microns	150 microns	200 microns	Average STD	STD Average Change
Base model	60.1	83.0	35.2	59.4	
2 inlets	74.2	89.1	34.4	65.9	-11%
Design 4	74.2	89.1	34.4	65.9	-11%

Table 13. Average standard deviation and change in percent with respect to the base model for high speed SS316L.

4.3.2 Increased Volume Flow Rate (500 LPM)

Given the superior standard deviation observed in the Discrete Phase Model (DPM) for the case involving 5 m/s inlet velocity in high-speed AlSi10Mg processing, an additional DPM analysis was conducted to affirm the superior performance of Design 4 over the base model. This section delves into the DPM results, specifically examining the standard deviations for the base model, configurations with two inlets, and Design 4.

1. High Velocity AlSi10Mg

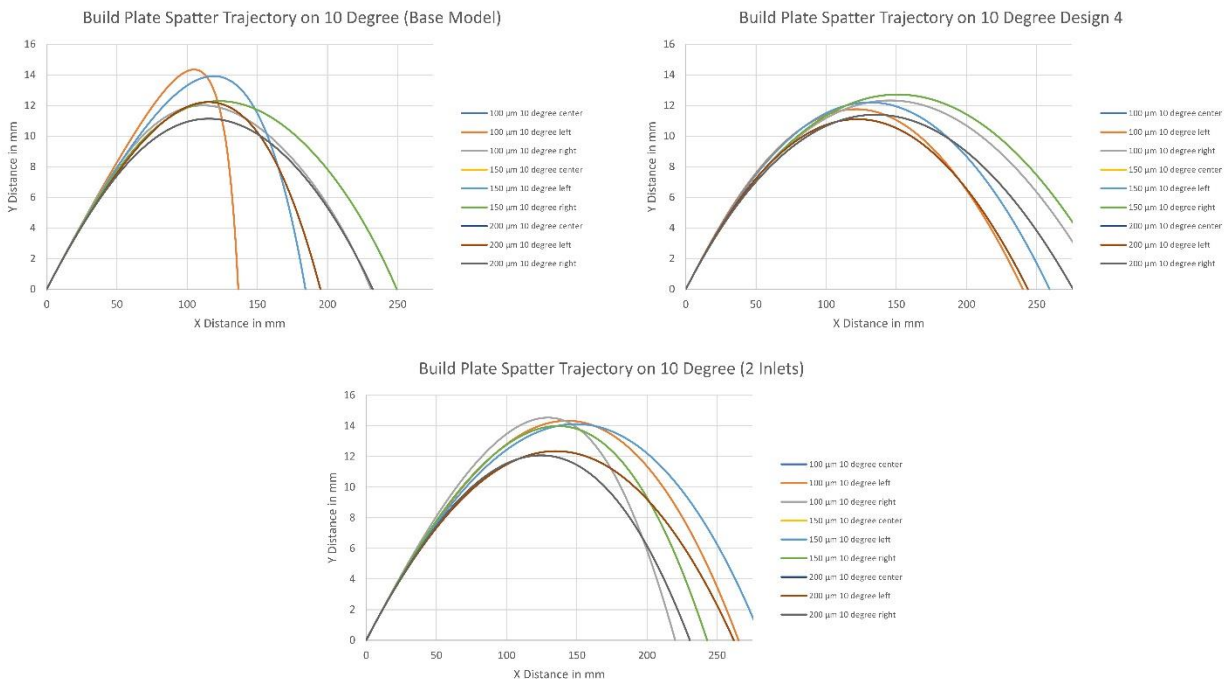


Figure 75. Comparison between base model, 2 inlets and design 4 for 10° ejection angle.

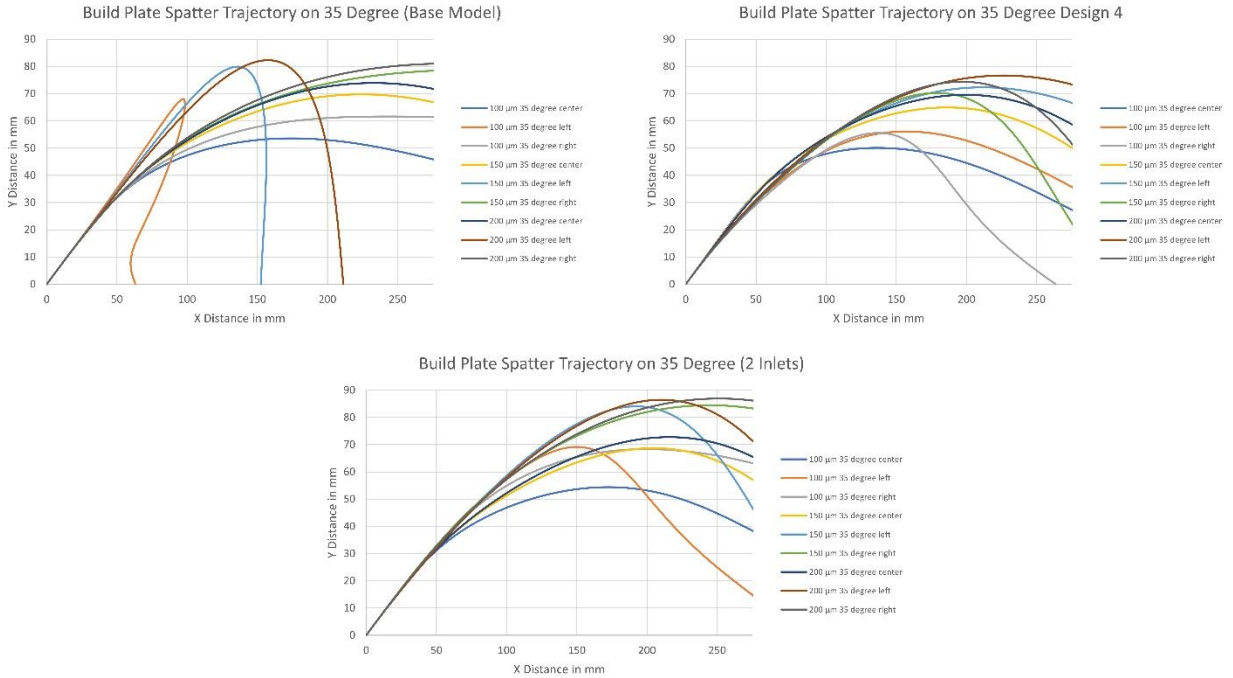


Figure 76. Comparison between base model, 2 inlets and design 4 for 35° ejection angle.

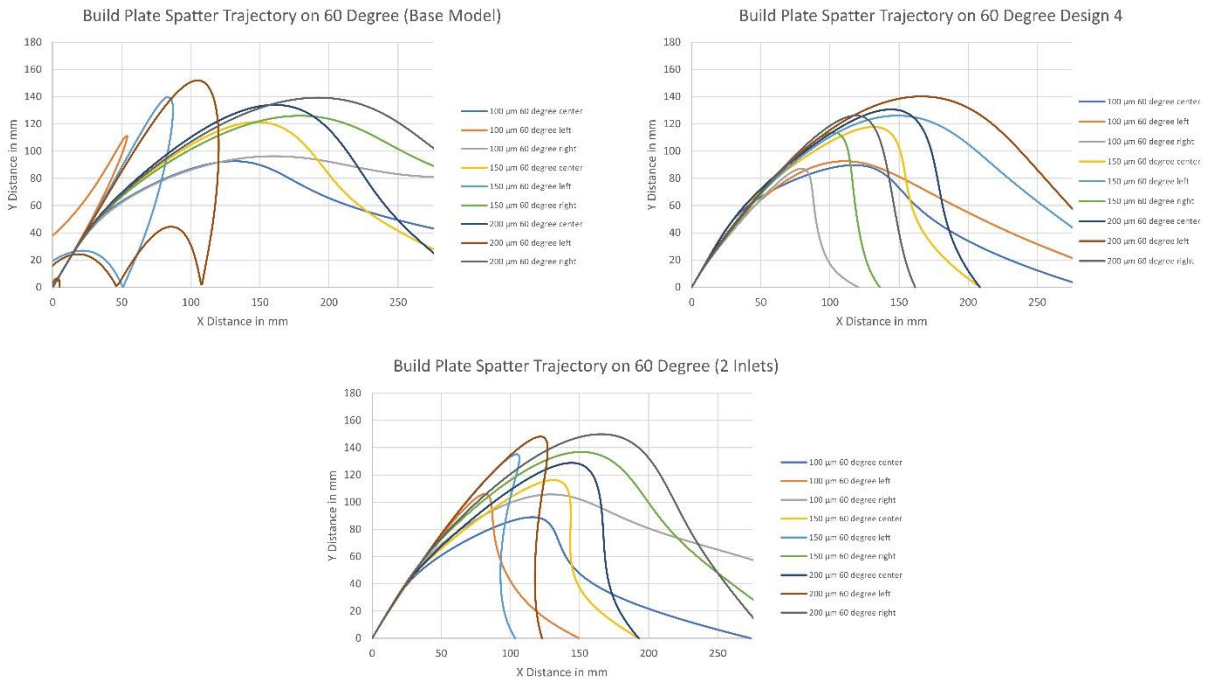


Figure 77. Comparison between base model, 2 inlets and design 4 for 60° ejection angle.

The standard deviation observed under the 10 m/s inlet condition corresponds with the earlier findings derived from the Discrete Phase Model (DPM). In this context, Design 4 consistently demonstrates superior performance in handling deviated spatters, as evidenced by standard deviation values of 83.2, 82.8, and 80.1 for spatter sizes of 100 μm , 150 μm , and 200 μm , respectively, as outlined in Table 14. In addition, the average standard deviation for design 4 excels both the base model and 2 inlets recording improvement by 30% over the base model and 10% over 2 inlet design.

Spatter size	100 microns				150 microns				200 microns			
Model	Min.	Max.	Mean	STD	Min.	Max.	Mean	STD	Min.	Max.	Mean	STD
Base model	54.0	394.9	246.0	128.5	87.0	446.3	273.0	118.0	120.2	431.5	278.6	103.5
2 inlets	149.6	472.5	296.0	94.1	106.6	361.3	272.8	83.2	127.0	472.5	282.3	103.5
Design 4	120.5	376.8	273.0	83.2	136.2	380.3	280.0	82.8	161.7	379.5	280.0	80.1

Table 14. Minimum and maximum spatter travelling distance, mean distance, and standard deviation for high speed AlSi10Mg.

Spatter size	100 microns	150 microns	200 microns	Average STD	STD Average Change
Base model	128.5	118.0	103.5	116.7	-
2 inlets	94.1	83.2	103.5	93.6	20%
Design 4	83.2	82.8	80.1	82.0	30%

Table 15. Average standard deviation and change in percent with respect to the base model for high speed AlSi10Mg.

2. High Velocity SS 316L

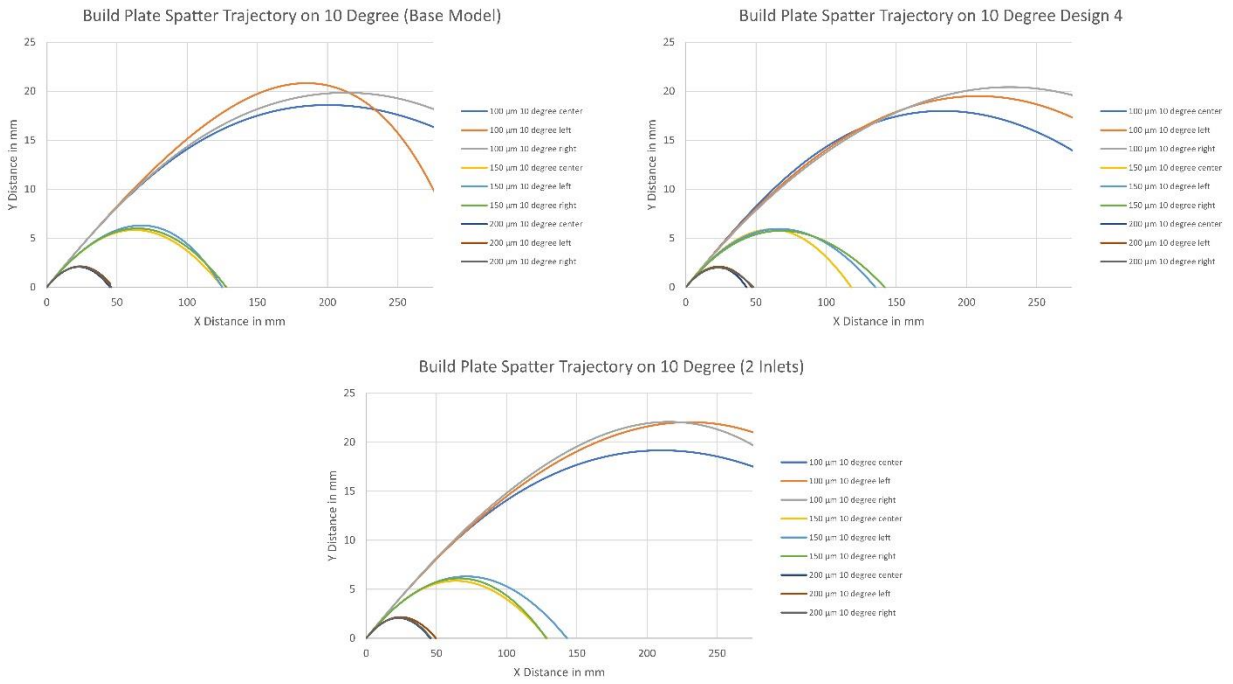


Figure 78. Comparison between base model, 2 inlets and design 4 for 10° ejection angle.

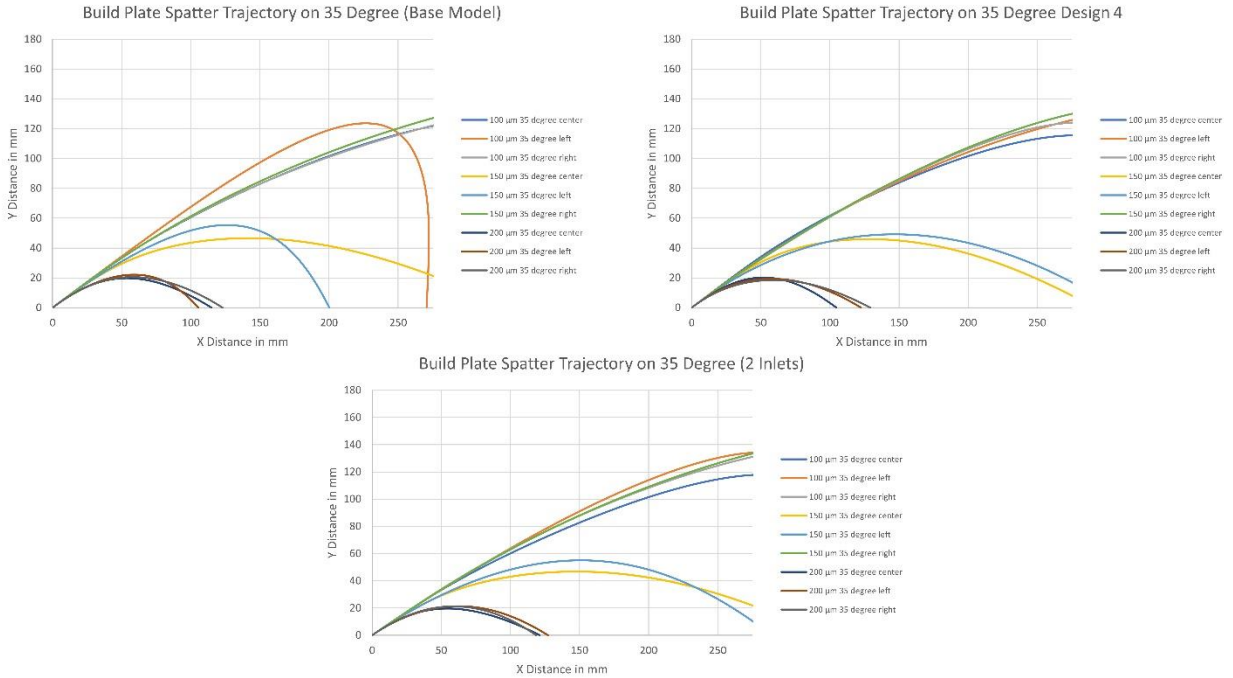


Figure 79. Comparison between base model, 2 inlets and design 4 for 35° ejection angle.

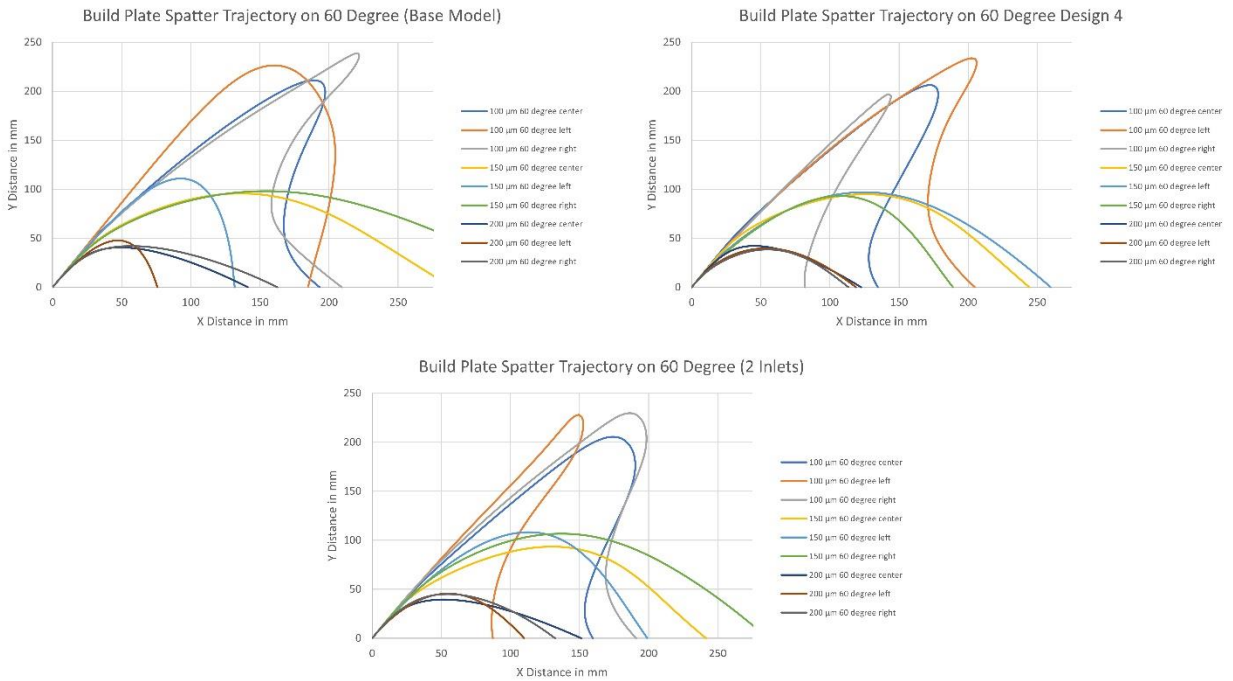


Figure 80. Comparison between base model, 2 inlets and design 4 for 60° ejection angle.

In the Discrete Phase Model (DPM) analysis of high viscosity SS316, Design 4 exhibits a comparable outcome to the 2 inlets and base model, with three spatters falling within the range of 100 mm to 150 mm. Notably, in the base model, a 150 μm spatter at a 35° angle lands on the build plate. Despite this, the base model demonstrates the lowest standard deviation among all models, registering 75.9 for 100 μm , as presented in Table 16. Conversely, the modification involving 2 inlets records a standard deviation of 88.2 for 150 μm , indicating a higher value. For 200 μm , Design 4 outperforms both models. Although design 4 exhibited higher standard deviation when the inlet velocity was set to 5m/s comparing to the base model, in the 10 m/s for the high speed SS316L, it excels the base model by 6% while the 2 inlets design recorded 8% improvement in the standard deviation implying that the flow rate plays crucial rule for the heavier material.

Spatter size	100 microns				150 microns				200 microns			
Model	Min.	Max.	Mean	STD	Min.	Max.	Mean	STD	Min.	Max.	Mean	STD
Base model	197.3	362.5	300.9	75.9	125.1	468.9	251.8	136.2	45.1	162.7	95.5	44.4
2 inlets	152.7	472.5	313.3	106.6	128.3	361.0	233.7	88.2	45.5	151.2	100.2	41.4
Design 4	144.2	475.5	322.7	115.1	117.9	379.1	229.4	89.4	43.3	129.3	94.5	36.8

Table 16. Minimum and maximum spatter travelling distance, mean distance, and standard deviation for high speed SS316L.

Spatter size	100 microns	150 microns	200 microns	Average STD	STD Average Change
Base model	75.9	136.2	44.4	85.5	-
2 inlets	106.6	88.2	41.4	78.7	8%
Design 4	115.1	89.4	36.8	80.5	6%

Table 17. Average standard deviation and change in percent with respect to the base model for high speed SS316L.

CHAPTER 5

CONCLUSION

In summary, Selective Laser Melting (SLM) has emerged as a transformative force in additive manufacturing, with its power to produce intricate parts with high precision. However, the process encounters challenges, one significant being the generation of spatter - unwanted molten droplets formed during the process, which can potentially affect the efficiency and quality of the final product.

An effective solution has been the incorporation of an inert gas flow, such as argon or nitrogen. These gases not only facilitate the removal of spatter but also maintain a non-reactive environment, inhibiting oxidation and preserving the integrity of the end product. Nevertheless, the optimization of this gas flow remains an area that warrants further exploration. The inert gas flow plays a vital role beyond just mitigating spatter issues. It influences numerous factors including thermal gradients, melt pool dynamics, and overall process stability. The choice of the gas used can significantly influence these factors, making it essential to strike a balance for optimal results. In the initial phase of our study, comprehensive simulations were conducted on the base model to validate our results with literature. Next, the exploration of geometric modifications focused on parameters such as fillet number and radius, nozzle length, discharge area, incline angles, orifice positions, inner diameters, number of orifices, and inlet headers to improve flow uniformity. The final design zeroed in on variations in the inlet nozzle, discharge area, and incline, while fillet modifications were excluded due to their impact on flow behavior based on the fillet radius. Some key results corresponding to different ejection speeds and spatter materials are presented below:

1. Low-Speed AlSi10Mg Material:

In the simulation of low-speed AlSi10Mg processing, particularly central spatter, the Discrete Phase Model (DPM) analysis highlights the superior efficacy of the base model in spatter elimination across varying particle sizes. Design 3 consistently outperforms both design 4 and the base model for spatter sizes of 100

μm , 150 μm , and 200 μm . Notably, for 100 μm spatter, the standard deviation of results for Design 3 is recorded as 10.2, while the base model and Design 4 exhibit standard deviations of 13.6 and 21.6, respectively. However, Design 4 exhibits a more uniform flow, recording the lowest standard deviation, suggesting potential for further optimization.

Under the 10 m/s inlet condition, Design 3 consistently demonstrates superior performance in handling deviated spatters recording 50% enhanced average standard deviation compared to Design 4 and the base model.

2. High-Speed AlSi10Mg Material:

In the Discrete Phase Model (DPM) analysis of high-speed AlSi10Mg, Design 4 exhibits comparable outcomes to Design 3, with both demonstrating effective spatter removal. Notably, Design 4 outperforms both the base model and design 3 showing improved average standard deviation of 30% over the base model and 2% over Design 3.

3. SS 316L Material Insights (Center, Left, and Right Spatters):

The Discrete Phase Model (DPM) analysis of SS 316L material reveals varying efficiencies of spatter removal for different designs and spatter locations. Design 3 shows specific strengths, especially in the removal of certain spatter sizes and ejection angles compared to Design 4, emphasizing the importance of understanding the strengths and weaknesses of each design for context-specific utilization in additive manufacturing processes.

4. Analysis Insights and Implications:

The study illuminates the substantial impact of material properties and ejection angles on spatter removal efficiency. This variation underscores the need for adaptable and customizable designs that can address the intricacies posed by different materials and ejection angles in additive manufacturing processes. Design 3 consistently displays narrower spatter landing ranges across various materials and angles than base model, suggesting its potential for more precise and controlled spatter removal.

These findings highlight the significant impact of design modifications on spatter removal efficiency and the complexity of flow dynamics within the chamber. Design 4 often outperforms the base model, especially in high-speed AlSi10Mg simulations and for specific spatter sizes and angles. Design 3 shows mixed performance but is notably effective in some scenarios. Further investigations and fine-tuning of the designs, including orifice placements and inlet header adjustments, are recommended to optimize spatter removal and flow dynamics, as well as to explore additional parameters like Reynolds number. The presented data provides a foundation for future research and improvements in the field, offering a nuanced understanding of the intricate relationship between design configurations and spatter removal efficiency in additive manufacturing processes.

CHAPTER 6

FUTURE WORK

6.1 Orifice

The orifice serves as a widely employed device in various industries for flow rate control. In the context of the current study, an imbalance in the flow within the chamber was identified, leading to a rightward shift in the flow profile, as depicted in the velocity contour of the base model. Consequently, three distinct modifications were introduced to the base model to address this imbalance.

The initial modification involved the incorporation of two orifices, each possessing an inner diameter of 29mm. The first orifice was strategically positioned in the inlet header after the 4th inlet nozzle, while the second orifice was placed following the 8TH nozzle. Also, in this modification, the thickness of the orifices was 8mm. This adjustment resulted in a pronounced leftward shift in the flow profile, as illustrated in Figure 82.

The second modification mirrored the first in terms of orifice configurations but differed in placement and diameter. Here, the inlet diameter was increased to 35mm, and the first and second orifices were situated after the 6th and 9th inlet nozzles, respectively. The thickness of the orifices was 2mm.

In this case, the flow profile did not shift, but a reduction in skewness was observed in the high-velocity region.

The final modification featured a single orifice with a 35mm inner diameter, strategically placed after the 7th inlet nozzle with a thickness of 2mm. Notably, the flow profile closely resembled that of the second configuration (35mm after the 6th and 9th inlet nozzles), albeit with a reduced level of skewness.

Future investigations are recommended to explore parameters such as orifice position, quantity, and inner diameter. It is noteworthy that the proposed modifications are not only effective in rectifying the flow imbalance but also relatively straightforward to implement in practical applications.

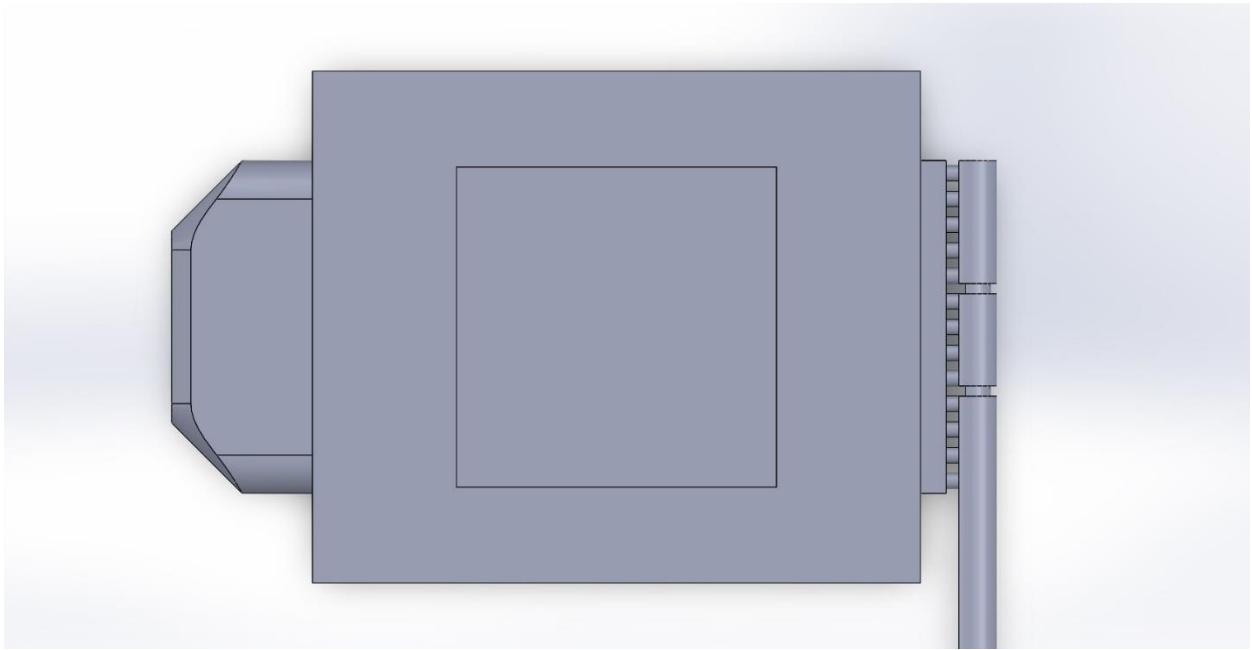


Figure 81. Two Orifices after the 6th and 9th inlet nozzles. 3D model with 8mm thickness.

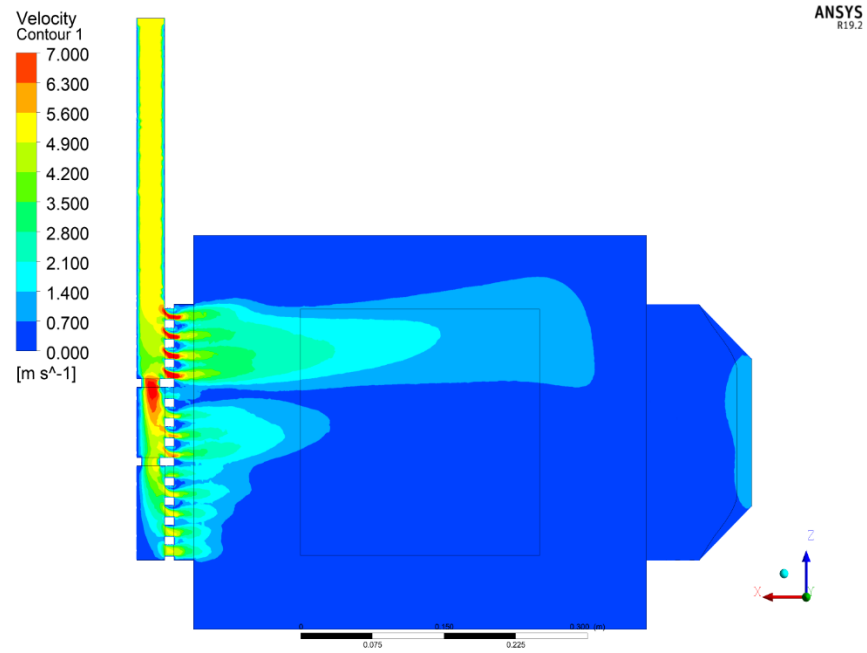


Figure 82. Velocity contour for two Orifices after the 6th and 9th inlet nozzles with 29mm inner diameter.

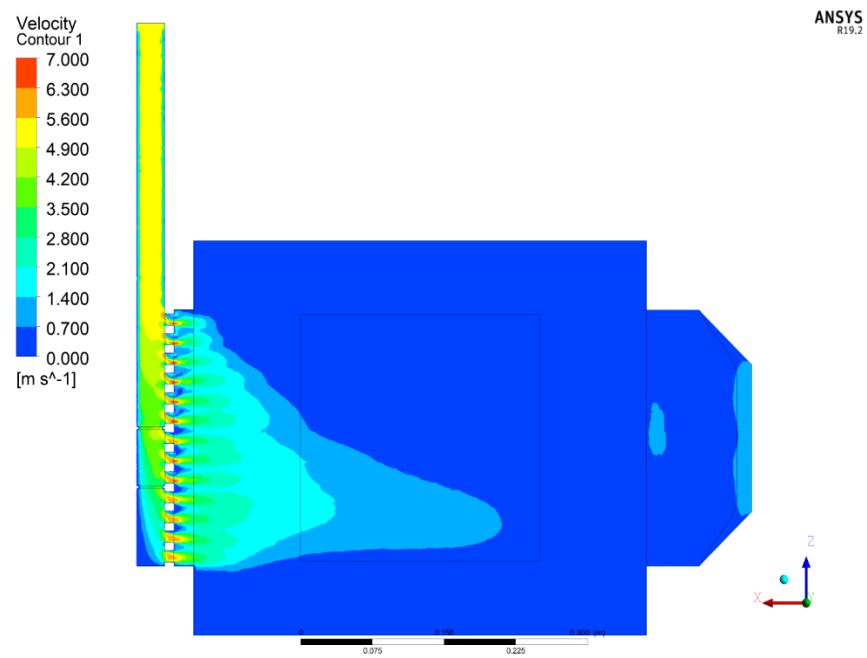


Figure 83. Velocity contour for two orifices after the 6th and 9th inlet nozzle with 35mm inner diameter with 2 mm thickness.

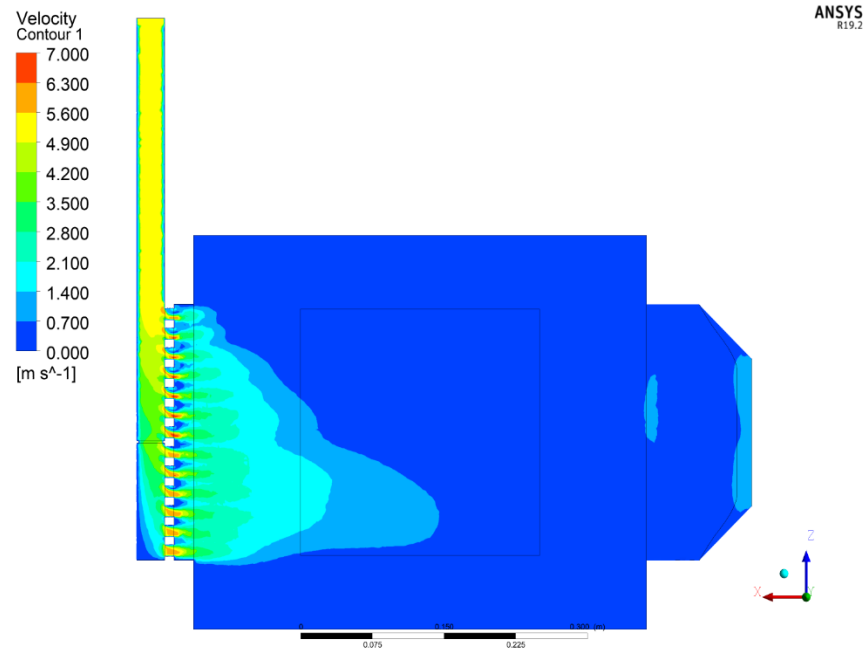


Figure 84. Velocity contour for one orifice after the 7th inlet nozzle with 2mm thickness.

6.2 Inlet Header

The modification involved the addition of three inlet headers to the base model, each with the same diameter as the inlet header in the base model. This adjustment resulted in an even more uniform flow. However, further investigation should be considered, particularly concerning the positions of the two inlet headers perpendicular to the base design's inlet header, as well as the diameters and lengths of these additional inlet headers. Delving into the details of these three modifications is recommended to enhance flow symmetry and gain a more comprehensive understanding of their impact on the overall flow dynamics within the chamber. It is also worth mentioning that considering the Reynolds number should remain the same when comparing the base model and the inlet headers. In this simulation, the Reynolds number was increased 2 times and 4 times for the 2 headers and 4 headers respectively since the inlet velocity remained the same (5 m/s) in each header).

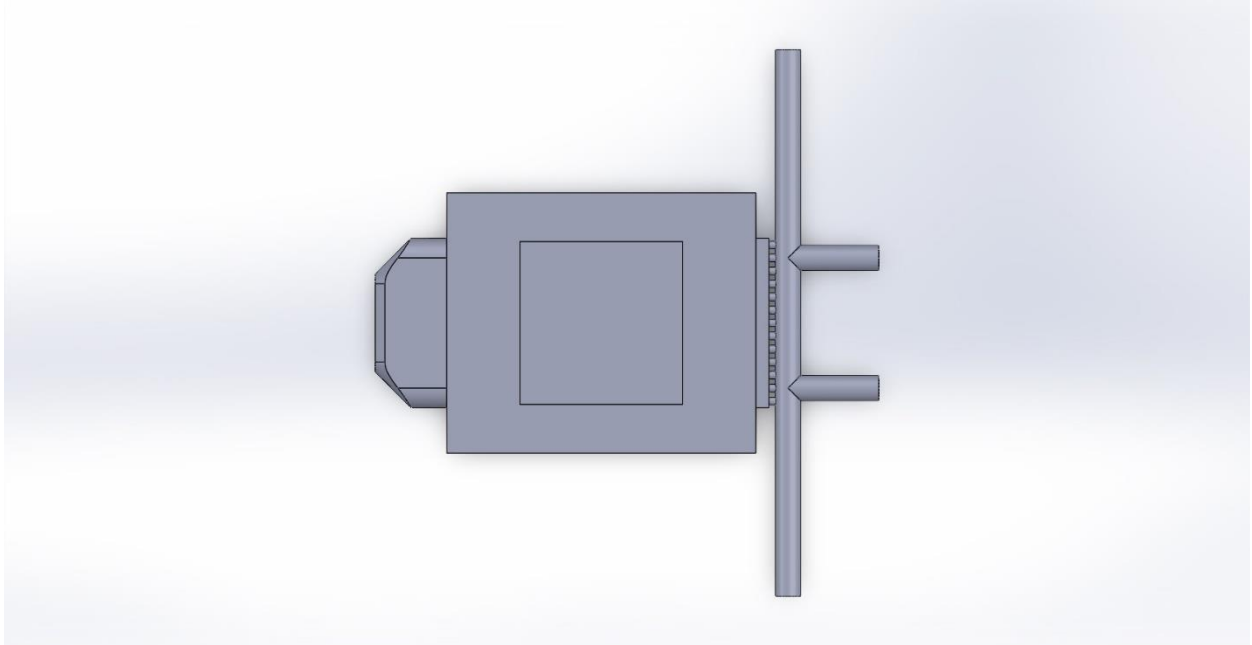


Figure 85. Base design with 4 inlet headers.

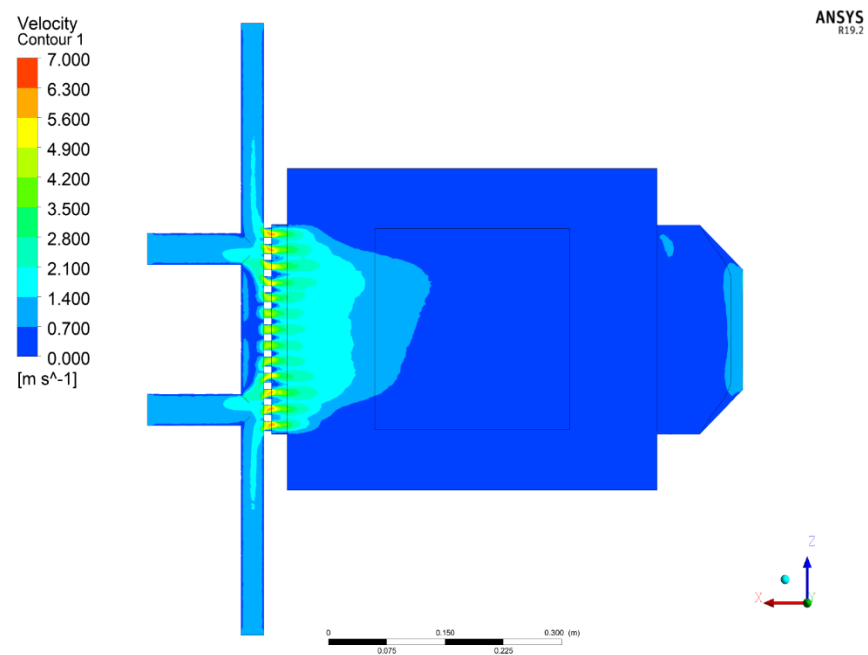


Figure 86. Base model with 4 inlet headers.

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Journal papers:

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2. **Ali I. Amailou**, Awad B.S. Alquaity, "Insights into Efficient Spatter Removal in SLM Build Chamber: A Numerical Approach", submitted to International Journal of Advanced Manufacturing Technology

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