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Research Article

Analysis of Laser Powder Bed Fusion (LPBF) Using Computational Fluid Dynamics (CFD)

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Abstract:

The metal additive manufacturing technique, Laser Powder Bed Fusion (LPBF), produces complex, precise components through widespread adoption. The process is substantially affected by gas flow dynamics that control both spatter removal, thermal distribution, and part quality. The research uses Computational Fluid Dynamics (CFD) simulations to analyse how bypass systems, nozzle configurations, and suction pressures affect LPBF chamber gas flow optimisation. The ANSYS Fluent software performed a comprehensive numerical evaluation to analyse velocity fields and pressure distributions and streamline patterns across different operational conditions. Implementing bypass systems leads to stabilised flow patterns by reducing recirculation zones and creating uniformity, enhancing melt pool consistency. Implementing optimised nozzles enhances flow efficiency by reducing turbulence while improving spatter ejection. The variation of suction pressure had a moderate effect on velocity distribution, but it proved essential for controlling chamber pressure and gas flow rate. The Coanda effect was observed to influence gas adherence to chamber surfaces, affecting thermal management. The research delivers necessary technical knowledge about LPBF gas flow system optimisation, leading to better manufacturing precision, reduced defects, and increased process dependability.

1. Introduction

Laser Powder Bed Fusion (LPBF) represents an additive manufacturing method that produces complex metal components through layer-by-layer fusion of metal powders. LPBF benefits the aerospace, automotive, and biomedical sectors by making lightweight, substantial parts that use as little material as possible[1], [2].

Overview of Additive Manufacturing

Additive Manufacturing (AM) goes by the name 3D printing in addition to its official designation. AM differs from traditional manufacturing since it builds components by adding layers on top rather than subtracting them from a larger block. The technology results in both minimal material waste and enhanced design flexibility. Among the AM technologies, LPBF is the most suitable to manufacture metal components with high precision and superior mechanical properties.

LPBF technology has received widespread adoption in industries where lightweight, high-performance materials are needed. Aerospace entities utilise LPBF technology to make complex turbine blades and structural components, while the medical sector employs it to create customised implants and prosthetics. The automotive industry makes use of LPBF technology to produce lightweight, high-strength parts that improve both vehicle performance and fuel economy.[3]

Working Principle of LPBF

LPBF functions through the controlled application of a laser beam, which melts and fuses metal powder particles to form solid metal parts. The main steps involved in the process are listed below:.[4], [5], [6]

1. Powder Spreading: Metal powder receives uniform coverage from a recoater in a thin layer on the build platform.
2. Laser Scanning and Melting: A digital CAD model directs the laser to precisely melt the selected areas of the powder layer.
3. Solidification and Cooling: The powdered material that has been melted experiences rapid cooling, which causes it to solidify while connecting to the previously formed layers.
4. Layer Repetition: The whole component is built through continuous repetition.
5. Part Removal and Post-Processing: The printing process ends when the part is removed to undergo heat treatment, followed by machining and surface finishing procedures

Importance of Process Optimization

LPBF brings numerous advantages but also multiple technical challenges that require optimisation. The performance of LPBF depends on several essential factors, which include:[7], [8], [9], [10]

- **Laser Power and Scan Speed:** Increased laser power penetration depth improves results but produces keyhole defects and excessive spatter. Achieving flawless builds requires finding the appropriate equilibrium between laser power levels and scanning velocities.
- **Powder Characteristics:** How powder materials behave during melting depends on their particle size distribution and shape and material properties, which affect bed packing density.
- **Gas Flow Management**: Proper gas flow functions to eliminate spatter and metal vapours, which helps prevent defects while maintaining part integrity.
- **Thermal Management:** Proper heat distribution helps reduce stress and distortion in the final product.

Role of Computational Fluid Dynamics (CFD) in LPBF

The robust simulation tool Computational Fluid Dynamics (CFD) models the LPBF process by analysing fluid flow heat transfer and phase changes. The use of CFD allows researchers and engineers to achieve the following goals:

- Prediction of melt pool dynamics for better laser scanning strategy optimisation.
- The assessment of gas movement patterns enables better spatter elimination and thermal control measures.
- Examining various nozzle structures and bypass systems for improved gas flow regularity.
- Analyze defect mechanisms and develop strategies for their prevention.

CFD simulations allow organisations to cut down on physical trial costs through efficient virtual experimentation. Developing high-performance computing systems has made computational fluid dynamics an essential optimisation tool for LPBF and additive manufacturing technology.[11], [12], [13], [14]

Applications of LPBF

LPBF technology provides diverse applications across multiple industrial sectors, such as aerospace, automotive and medical.[15], [16], [17], [18]

- Aerospace: The technology allows for creating lightweight yet strong turbine blades, engine components, and structural parts.
- Automotive: Custom high-performance parts are produced through this process to improve fuel efficiency and enhance vehicle durability.
- Medical: The medical field produces customised implants, prosthetics, and surgical instruments.
- Energy: Complex heat exchangers, fuel cells, and power generation components are developed using this technology.

Challenges and Future Directions

Despite its advantages, LPBF faces several technical challenges:

- The manufacturing challenges of porosity, cracking, and warping are still prevalent and require improvement.
- Materials are unsuitable for LPBF due to their thermal properties and oxidation behaviour.
- Many LPBF parts must be subject to significant post-processing to meet industry requirements.

Future research includes increasing the efficiency of LPBF by using AI to optimise the process, monitoring the process in real-time and allowing multi-material printing. With continued advancements, LPBF will likely change modern manufacturing in many industries.

2. Literature Review

Gas Flow and Thermal Management in LPBF

LPBF thermal management and gas flow systems play a crucial role in LPBF as the two are related to LPBF process parameters. It is essential to create a gas flow system that will distribute the heat evenly, remove the spatter well, and reduce the oxidation of metal powder. Some studies have been conducted to determine the effect of gas flow on the LPBF process.[19], [20], [21]

The influence of gas flow speed and direction on the melt pool stability. It has been observed from their results that an optimised flow field decreases turbulence and improves the uniformity of the powder bed, which is essential for minimising defects such as porosity and incomplete fusion[22]. The effects of changing gas suction pressures at the outlet, which revealed that increased suction increases spatter removal and leaves the building area cleaner[23].

Influence of Nozzle Design on Gas Flow

The LPBF chamber gas flow distribution depends heavily on nozzle configuration. In their study they tested various nozzle shapes, such as rectangular, triangular, and circular. They found that triangular nozzles produce a more symmetrical flow pattern, thus minimising turbulence and enhancing powder removal. On the other hand, rectangular nozzles created localised high-velocity zones that caused material shifting and nonuniform heating[24].

The further research on multi-nozzle arrangements to improve flow uniformity. The study conducted by these authors showed that the staggered placement of nozzles produces improved gas velocity profiles that help to reduce backflow effects and create a stable melt pool. It can be concluded from these findings that nozzle optimisation is crucial to enhancing the overall LPBF efficiency[25].

Bypass Systems and Pressure Regulation

The bypass channels in LPBF systems control the pressure distribution and eliminate the unwanted recirculation areas. The research established that incorporating bypass enhances spatter removal and promotes a stable build environment by preventing flow stagnation. Their study also revealed that a properly adjusted bypass system decreases the pressure fluctuations, thus resulting in more homogenous melt pool formation[26].

Furthermore, the correlation between bypass configuration and energy efficiency. The authors established that well-placed bypass channels decrease energy usage by adjusting the gas flow rates, thus making the LPBF manufacturing process more energy efficient[27].

Computational Fluid Dynamics (CFD) in LPBF Research

The application of Computational Fluid Dynamics (CFD) is now considered one of the most essential tools in the analysis of the LPBF process parameters. It is possible to predict fluid motion through CFD simulations, investigate heat transfer phenomena and design system layouts prior to experimental verification. The study reviewed the latest developments in CFD modelling for LPBF and stressed the necessity of turbulence models, boundary conditions, and mesh refinement to obtain reliable results.[28]

Furthermore, CFD analyses used real-time data to validate the accuracy of the simulation, thus providing a link between theoretical modelling and practical implementation. The research also showed that CFD-driven process improvements result in substantial gains in print precision, mechanical characteristics, and defect control[29], [30-32].

From the literature review, it can be deduced that gas flow management, nozzle design, bypass systems and CFD modelling are critical for improving the LPBF processes. Research has given helpful information on enhancing the quality of parts and increasing manufacturing efficiency by improving fluid dynamics and thermal control methods. Future research should use artificial intelligence in conjunction with CFD simulations to make fundamental time changes in the process and enhance the reliability of LPBF technology.

3. Methodology

This study comprehensively analyses gas flow dynamics and thermal behaviour in LPBF using CFD simulations. The process starts with defining the computational domain in which a three-dimensional model of the LPBF chamber with the powder bed, the laser source, and the gas flow inlet and outlet is established. The domain is discretised with a fine mesh to capture the details of flow, temperature and phase distribution.

Process Parameters Considered

Several key process parameters are considered to obtain accurate CFD simulation results relevant to the practical LPBF operations. These parameters include:

- Laser Power: Varying from 200 W to 500 W to define the melt pool's depth and width.
- Scanning speed, between 100 mm/s and 1200 mm/s, to control the heat input and the material consolidation.
- Layer thickness from 20 µm to 50 µm determines the resolution and build rate.
- Spot size from 50 µm to 100 µm influences the energy distribution.
- Gas flow rate from 5 m/s to 15 m/s, for an efficient spatter removal and thermal control.
- Suction pressure, from 1600 Pa to 2000 Pa, to control the chamber pressure and the clearance of the spatter.

Mesh Generation and Boundary Conditions

For a precise simulation, a structured and refined mesh is defined to reach a good balance between the computational cost and the mesh size. Adaptive meshing techniques are applied to create a mesh with a finer grid in areas with steep temperature gradients and fluid flow changes.

The boundary conditions are one of the most critical factors affecting CFD simulations' accuracy. The main boundary conditions applied in this study are:

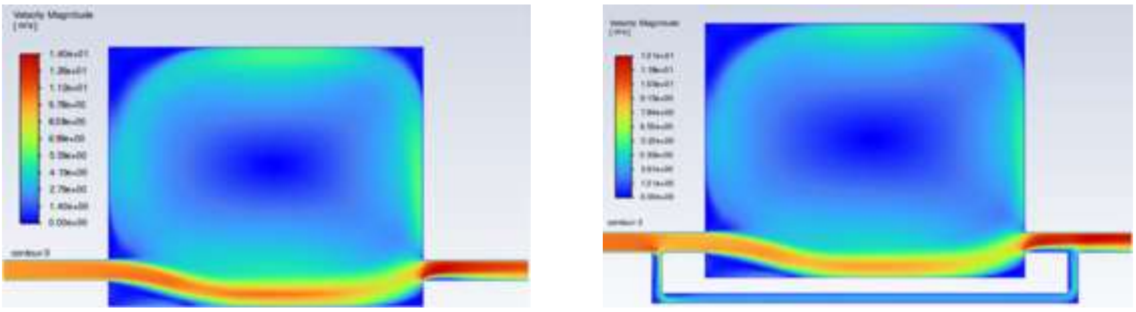
- Inlet velocity: A constant gas inlet velocity of 10 m/s to mimic actual LPBF chamber conditions.
- Outlet pressure: The suction pressures of 1600 Pa to 2000 Pa to study the effect on gas flow patterns.
- Adiabatic walls: The external heat loss is assumed to be prevented, so the thermal consistency is maintained.
- Heat source model: A Gaussian heat distribution is used to model the laser interaction with the powder bed.

ANSYS Fluent, a well-known CFD software, is used to solve the governing equations: the conservation of mass, momentum (Navier-Stokes equations) and energy. The Volume of Fluid (VOF) method is used to capture the interface between solid and liquid phases, and the k-epsilon turbulence model is used to model the complex flow behaviours caused by gas circulation. Multiple simulation cases are conducted to determine the effects of nozzle geometries, bypass configurations, and gas flow rates on melt pool stability, spatter removal efficiency, and thermal uniformity. The simulations extract velocity profiles, pressure distributions, temperature gradients, and melt pool dimensions for analysis. The results are validated by comparing them with experimental data from previous studies to ensure the reliability of the numerical predictions. Furthermore, sensitivity analyses are conducted to determine the effect of varying process parameters on the gas flow and thermal behaviour. The results from this methodology offer significant benefits for optimising LPBF systems by enhancing gas flow homogeneity, decreasing defects, and increasing energy efficiency. This application of CFD provides a low-cost and efficient approach to examining process dynamics, thereby reducing the requirement for extensive physical experimentation and permitting parametric studies to improve LPBF operation. Enhancements to this methodology in the future could include the integration of machine learning algorithms for objective time process optimisation and multi-material simulations to increase the applicability of LPBF to advanced manufacturing domains.

4. Results and Discussion

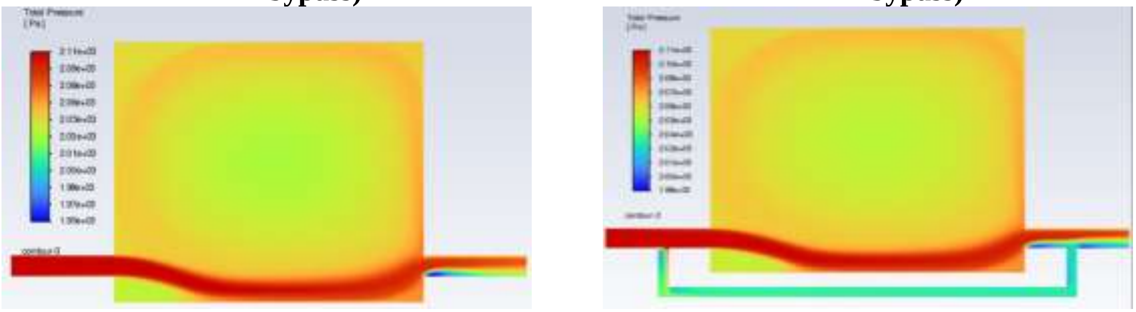
Velocity, Pressure, and Streamline Contours (With and Without Bypass)

The velocity pressure and streamline contours of systems with and without bypass channels are shown in Figure 1. The simulation results show that gas circulation within the build chamber is significantly higher when no bypass exists. The maximum velocity recorded without a bypass is 14 m/s, whereas with a bypass, the maximum velocity reduces slightly to 13.1 m/s. This implies bypass systems help control and stabilise the gas flow and reduce turbulence. Furthermore, the outlet velocity increases when a bypass is used, from 11.1 m/s (without bypass) to 11.3 m/s (with bypass), which means that the bypass decreases recirculation and increases the uniformity of the flow. The pressure distribution shows that without a bypass, there is a more significant pressure drop



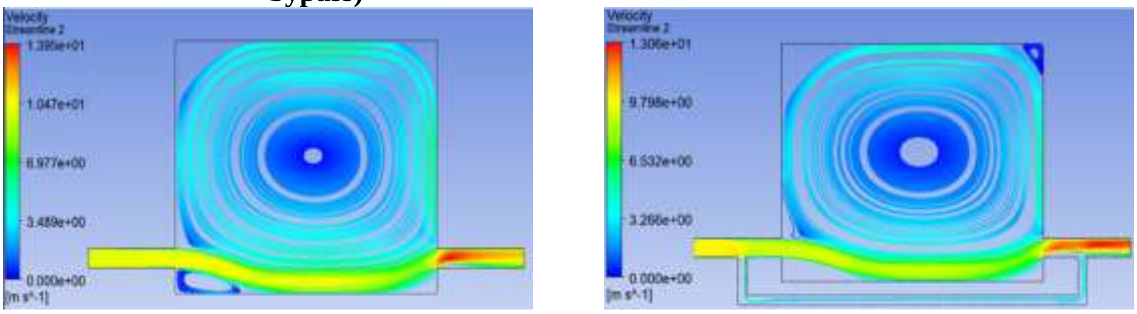
a. Velocity magnitude in m/s (without bypass)

b. Velocity magnitude in m/s (with bypass)



c. Pressure contour in pa (Without bypass)

d. Pressure contour in pa (With bypass)



e. Velocity Stream line contour in m/s (without bypass)

f. Velocity Stream line contour in m/s (with bypass)

Figure. 1. *a to f represents Velocity, Pressure, and Streamline Contours (With and Without Bypass) without a nozzle.*

across the chamber, which causes flow disturbances. The streamlines in the system without a bypass show stronger vortices near the powder bed, which can lead to spatter redeposition and surface defects. On the other hand, a bypass significantly reduces these vortices, resulting in a more stable gas flow.

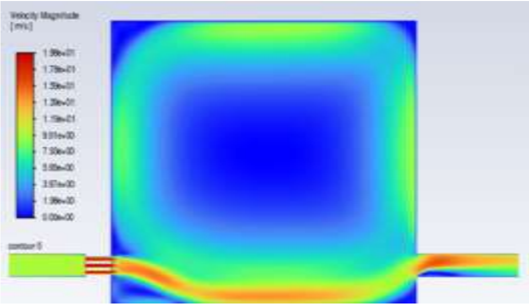
Effect of Nozzles on Gas Flow (With and Without Bypass)

The comparison between gas flow dynamics in a system with rectangular nozzles, both with and without a bypass, is presented in Figure 2. The results show that the introduction of nozzles changes the flow structure by increasing the localised velocities. The maximum velocity near the nozzles is 19.8 m/s without a bypass, but with a bypass, it is 15.1 m/s. The decrease in peak velocity with a bypass indicates that the system has a more uniform flow profile, which reduces localised disturbances and potential spatter adhesion.

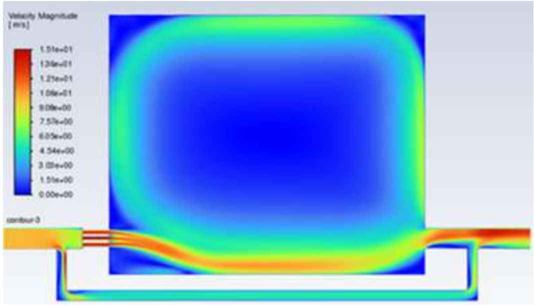
The streamlines further show that gas circulation is higher in the system without a bypass, which means the turbulence is higher. The pressure at the inlet is higher in the non-bypass system, which could result in more significant fluctuations in the melt pool dynamics. The bypass system helps control the pressure gradient, making the powder fusion process more stable.

Impact of Nozzle Geometry on Flow Uniformity

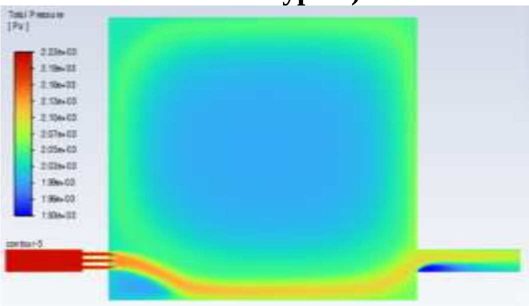
The comparison between systems using rectangular and triangular nozzle geometries appears in Figure 3. The velocity distribution changes when the triangular nozzle configuration replaces the previous setup by dividing the four nozzles evenly. The velocity field becomes more uniform through triangular nozzles, which helps minimise excessive turbulence. The velocity contours show small circulation zones that form at the base of the chamber, especially in the bottom-left area, because a low-pressure zone develops from the increased air volume. The recirculation needs to be considered during nozzle placement optimisation.



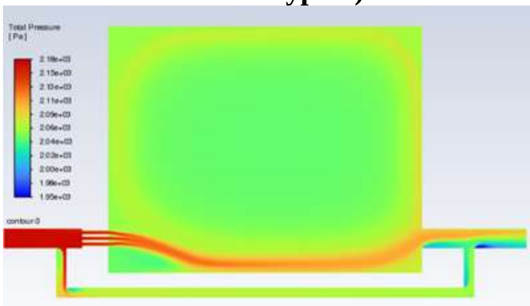
a. Velocity magnitude in m/s (without bypass)



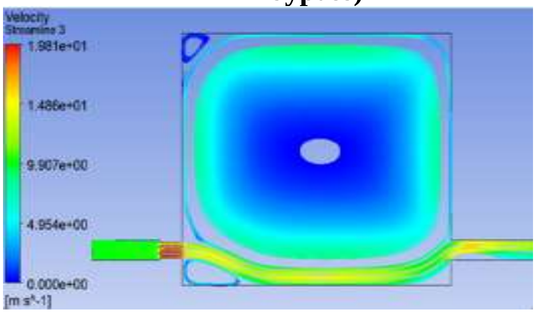
b. Velocity magnitude in m/s (with bypass)



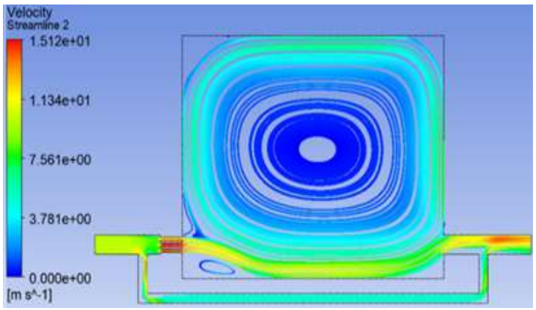
c. Pressure contour in pa (Without bypass)



d. Pressure contour in pa (With bypass)

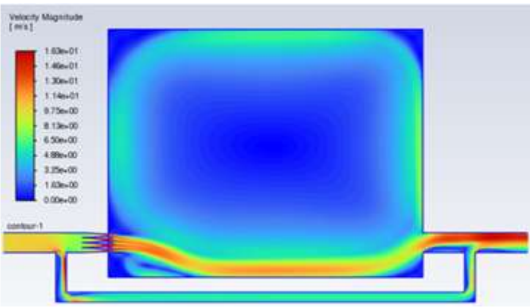


e. Velocity Stream line contour in m/s (without bypass)

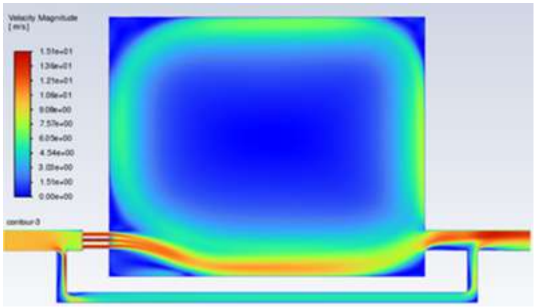


f. Velocity Stream line contour in m/s (with bypass)

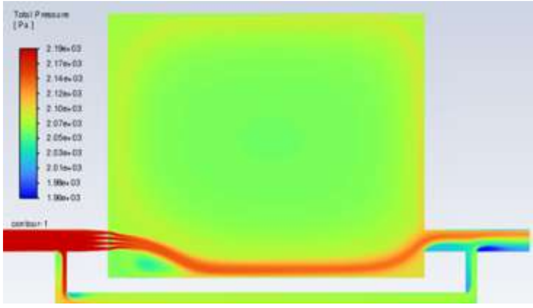
Figure. 2. *a to f represents Velocity, Pressure, and Streamline Contours (With and Without Bypass), respectively, with rectangular nozzle*



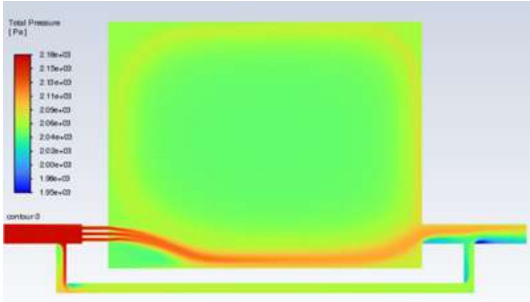
a. Velocity magnitude in m/s for triangular nozzle



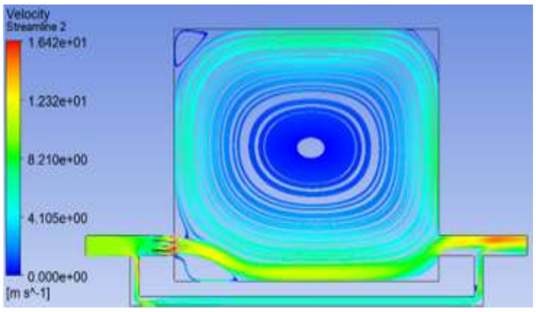
b. Velocity magnitude in m/s for rectangular nozzle



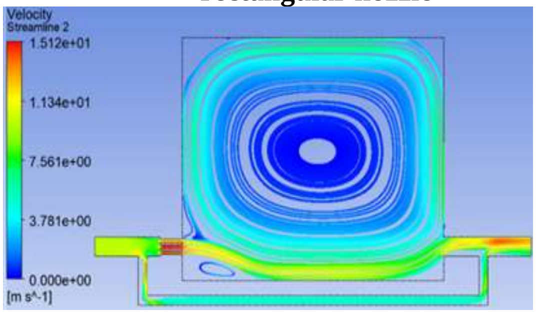
c. Pressure contour in pa for triangular nozzle



d. Pressure contour in pa for rectangular nozzle



e. Velocity Stream line contour in m/s for triangular nozzle



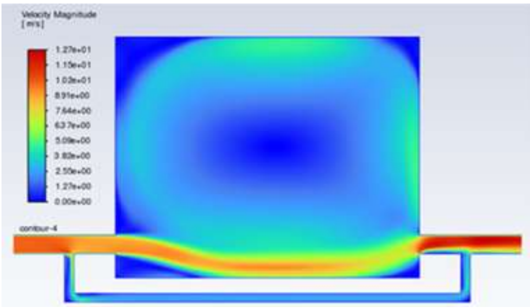
f. Velocity Stream line contour in m/s for rectangular nozzle

Figure. 3. *a,c,e and b,d,f represent Velocity, Pressure, and Streamline Contours with triangular and rectangular nozzles, respectively*

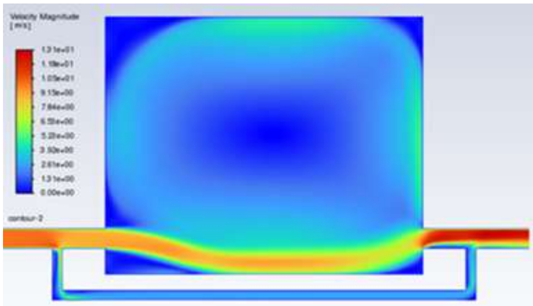
The triangular nozzles improve the efficiency of spatter removal. The rectangular nozzles, in comparison, restrict the flow between nozzle gaps and create acceleration zones with higher velocities. This constriction increases flow resistance and may result in inconsistent spatter removal.

Effect of Suction Pressure on Gas Flow (With Bypass)

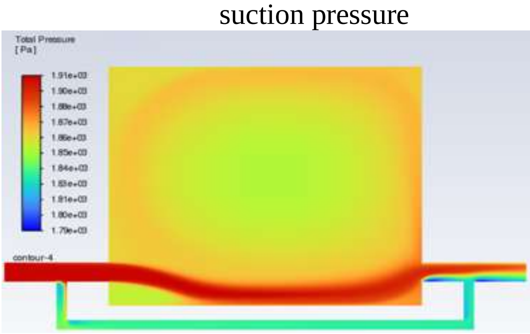
The results of Figure 4 show how changes in the suction pressure affect the gas flow in the bypass system when pressures of 1800 Pa and 1600 Pa are used. The results show that there is not much difference in the overall flow pattern, with only a tiny difference in the maximum velocity values. The peak velocity for 1800 Pa suction pressure is 12.7 m/s, while for 1600 Pa suction pressure, it is slightly higher at 13.1 m/s. The maximum total pressure for 1800 Pa suction pressure is 1910 Pa, while that for 1600 Pa suction pressure is 1710 Pa.

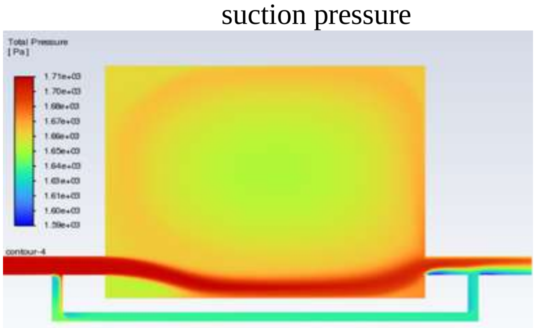


a. Velocity magnitude in m/s for 1800 pa suction pressure



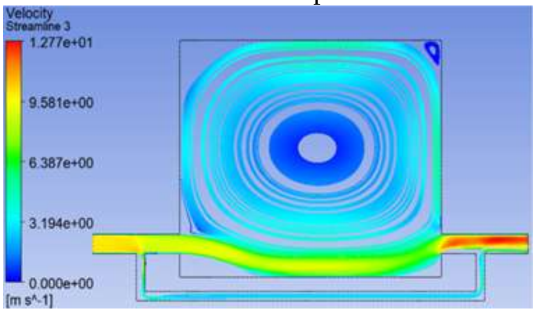
b. Velocity magnitude in m/s for 1600 pa suction pressure



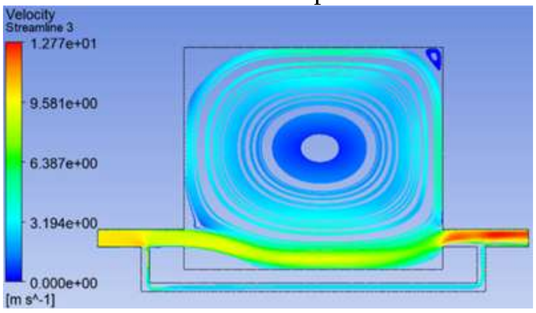


c. Pressure contour in pa for 1800 pa suction pressure

d. Pressure contour in pa for 1600 pa suction pressure



e. Velocity Stream line contour in m/s for 1800 pa suction pressure



f. Velocity Stream line contour in m/s for 1600 pa suction pressure

Figure. 4. *a,c,e and b,d,f represent Velocity, Pressure, and Streamline for 1800 and 1600 pa suction pressure respectively*

The bypass system shows a consistent flow structure across both suction pressure values with minimal fluctuations in flow velocity. The analysis indicates that suction pressure affects the chamber pressure gradient but has a negligible effect on velocity distribution in the studied range.

Coanda Effect on Gas Flow Dynamics

All simulations demonstrate the Coanda effect, which describes how gas flow sticks to the base of the build chamber because of pressure differences that develop near the powder bed. Bypass systems enhance gas streamlining by reducing turbulent recirculation zones, thus making the Coanda effect more noticeable. The Coanda effect plays a crucial role because the strong surface attachment of gas flow affects both melt pool stability and spatter removal efficiency.

Summary of Findings

- The bypass system implementation cuts down gas circulation while controlling velocity fluctuations and creating uniform gas flow distribution.
- The implementation of nozzles with triangular geometry enhances flow efficiency and spatter removal while minimising turbulence.
- The pressure difference between 1800 Pa and 1600 Pa causes slight variations in the chamber's velocity and pressure distribution patterns.
- The Coanda effect strongly influences gas flow attachment to chamber surfaces, affecting both spatter removal and thermal uniformity.

The research results provide essential information for LPBF gas flow optimisation, leading to better part quality and process stability.

5. Conclusion

The research delivers an extensive computational fluid dynamics (CFD) evaluation of LPBF systems to analyse how bypass systems nozzle configurations and suction pressure changes affect system stability and operational efficiency. The research shows that adding a bypass system produces uniform gas flow while minimising turbulent recirculation zones and enhancing spatter removal performance. The study indicates that nozzle geometry effectively controls velocity fields because triangular nozzles create better flow stabilisation and lower high-velocity areas than rectangular ones. The survey of suction pressure variations shows that velocity distribution changes moderately, but the system requires suction pressure to maintain LPBF chamber stability. The Coanda effect demonstrates how gas sticks to chamber surfaces, which requires optimising flow paths to achieve stable melt pool conditions and effective spatter mitigation. The research findings support LPBF system development by showing that gas flow optimisation produces better part quality, reduced defects, and improved thermal management. Future research should integrate real-time monitoring systems with machine learning control algorithms to optimise gas flow parameters in industrial LPBF applications.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

References

[1] L. Ladani and M. Sadeghilaridjani, "Review of Powder Bed Fusion Additive Manufacturing for Metals," *Metals 2021, Vol. 11, Page 1391*, vol. 11, no. 9, p. 1391, Sep. 2021, doi: 10.3390/MET11091391.

[2] S. R. Narasimharaju *et al.*, "A comprehensive review on laser powder bed fusion of steels: Processing, microstructure, defects and control methods, mechanical properties, current challenges and future trends," *J Manuf Process*, vol. 75, pp. 375–414, Mar. 2022, doi: 10.1016/J.JMAPRO.2021.12.033.

[3] M. Armstrong, H. Mehrabi, and N. Naveed, "An overview of modern metal additive manufacturing technology," *J Manuf Process*, vol. 84, pp. 1001–1029, Dec. 2022, doi: 10.1016/J.JMAPRO.2022.10.060.

[4] E. Santecchia, S. Spigarelli, and M. Cabibbo, "Material Reuse in Laser Powder Bed Fusion: Side Effects of the Laser—Metal Powder Interaction," *Metals 2020, Vol. 10, Page 341*, vol. 10, no. 3, p. 341, Mar. 2020, doi: 10.3390/MET10030341.

[5] J. D. Roehling *et al.*, "Physics of large-area pulsed laser powder bed fusion," *Addit Manuf*, vol. 46, p. 102186, Oct. 2021, doi: 10.1016/J.ADDMA.2021.102186.

[6] N. Alinejadian, L. Kollo, and I. Odnevall, "Progress in additive manufacturing of MoS2-based structures for energy storage applications – A review," *Mater Sci Semicond Process*, vol. 139, Mar. 2022, doi: 10.1016/j.mssp.2021.106331.

[7] P. V. Cobbinah, R. A. Nzeukou, O. T. Onawale, and W. R. Matizamhuka, "Laser Powder Bed Fusion of Potential Superalloys: A Review," *Metals 2021, Vol. 11, Page 58*, vol. 11, no. 1, p. 58, Dec. 2020, doi: 10.3390/MET11010058.

[8] S. Sanchez, A. Zafari, L. Caprio, A. G. Demir, and D. Jafari, "Temporal and Spatial Beam Shaping in LPBF for Fine and Porous Ti-Alloy Structures for Regenerative Fuel Cell Applications," *Lasers in Manufacturing and Materials Processing*, vol. 11, no. 1, pp. 154–178, Mar. 2024, doi: 10.1007/S40516-023-00244-3/FIGURES/13.

[9] J. Wang, R. Zhu, Y. Liu, and L. Zhang, "Understanding melt pool characteristics in laser powder bed fusion: An overview of single- and multi-track melt pools for process optimization," *Advanced Powder Materials*, vol. 2, no. 4, p. 100137, Oct. 2023, doi: 10.1016/J.APMATE.2023.100137.

[10] S. Chowdhury *et al.*, "Laser powder bed fusion: a state-of-the-art review of the technology, materials, properties & defects, and numerical modelling," *Journal of Materials Research and Technology*, vol. 20, pp. 2109–2172, Sep. 2022, doi: 10.1016/J.JMRT.2022.07.121.

[11] E. De Leon, A. Riensche, B. D. Bevans, C. Billings, Z. Siddique, and Y. Liu, "A Review of Modeling, Simulation, and Process Qualification of Additively Manufactured Metal Components via the Laser Powder Bed Fusion Method," *Journal of Manufacturing and Materials Processing 2025, Vol. 9, Page 22*, vol. 9, no. 1, p. 22, Jan. 2025, doi: 10.3390/JMMP9010022.

[12] M. A. Mahmood, A. U. Rehman, F. Pitir, M. U. Salamci, and I. N. Mihailescu, "Laser Melting Deposition Additive Manufacturing of Ti6Al4V Biomedical Alloy: Mesoscopic In-Situ Flow Field Mapping via Computational Fluid Dynamics and Analytical Modelling with Empirical Testing," *Materials 2021, Vol. 14, Page 7749*, vol. 14, no. 24, p. 7749, Dec. 2021, doi: 10.3390/MA14247749.

[13] T. Yu and J. Zhao, "Quantitative simulation of selective laser melting of metals enabled by new high-fidelity multiphase, multiphysics computational tool," *Comput Methods Appl Mech Eng*, vol. 399, p. 115422, Sep. 2022, doi: 10.1016/J.CMA.2022.115422.

[14] Y. Hu *et al.*, "Multi-physics modeling for laser powder bed fusion process of NiTi shape memory alloy," *J Alloys Compd*, vol. 954, p. 170207, Sep. 2023, doi: 10.1016/J.JALLCOM.2023.170207.

[15] U. Chadha *et al.*, "Powder Bed Fusion via Machine Learning-Enabled Approaches," *Complexity*, vol. 2023, no. 1, p. 9481790, Jan. 2023, doi: 10.1155/2023/9481790.

[16] R. Rahmani, B. Bashiri, S. I. Lopes, A. Hussain, H. S. Maurya, and R. Vilu, "Sustainable Additive Manufacturing: An Overview on Life Cycle Impacts and Cost Efficiency of Laser Powder Bed Fusion," *Journal of Manufacturing and Materials Processing 2025, Vol. 9, Page 18*, vol. 9, no. 1, p. 18, Jan. 2025, doi: 10.3390/JMMP9010018.

[17] N. Khan and A. Riccio, "A systematic review of design for additive manufacturing of aerospace lattice structures: Current trends and future directions," *Progress in Aerospace Sciences*, vol. 149, p. 101021, Aug. 2024, doi: 10.1016/J.PAEROSCI.2024.101021.

[18] U. Chadha *et al.*, "Powder Bed Fusion via Machine Learning-Enabled Approaches," *Complexity*, vol. 2023, no. 1, p. 9481790, Jan. 2023, doi: 10.1155/2023/9481790.

[19] N. D. Dejene and H. G. Lemu, "Current Status and Challenges of Powder Bed Fusion-Based Metal Additive Manufacturing: Literature Review," *Metals 2023, Vol. 13, Page 424*, vol. 13, no. 2, p. 424, Feb. 2023, doi: 10.3390/MET13020424.

[20] A. Ullah, M. Shah, Z. Ali, K. Asami, A. Ur Rehman, and C. Emmelmann, "Additive manufacturing of ceramics via the laser powder bed fusion process," *Int J Appl Ceram Technol*, p. e15087, 2025, doi: 10.1111/IJAC.15087.

[21] S. R. Narasimharaju *et al.*, "A comprehensive review on laser powder bed fusion of steels: Processing, microstructure, defects and control methods, mechanical properties, current challenges and future trends," *J Manuf Process*, vol. 75, pp. 375–414, Mar. 2022, doi: 10.1016/J.JMAPRO.2021.12.033.

[22] N. O'Brien, S. Z. Uddin, J. Weaver, J. Jones, S. Singh, and J. Beuth, "Computational analysis and experiments of spatter transport in a laser powder bed fusion machine," *Addit Manuf*, vol. 84, p. 104133, Mar. 2024, doi: 10.1016/J.ADDMA.2024.104133.

[23] W. Abd-Elaziem, S. Elkatatny, T. A. Sebaey, M. A. Darwish, M. A. Abd El-Baky, and A. hamada, "Machine learning for advancing laser powder bed fusion of stainless steel," *Journal of Materials Research and Technology*, vol. 30, pp. 4986–5016, May 2024, doi: 10.1016/J.JMRT.2024.04.130.

[24] T. Dahmen, "General rights Additive Manufacturing for Fuel Injectors: Design, Processes and Materials."

[25] H. Deng, Z. Wang, J. Wang, and H. Li, "Flow and heat transfer in a rotating channel with impingement cooling and film extraction," *Int J Heat Mass Transf*, vol. 180, p. 121751, Dec. 2021, doi: 10.1016/J.IJHEATMASSTRANSFER.2021.121751.

[26] J. Hoffmann and M. P. Venter, Proceeding of the 13th South African Conference on Computational and Applied Mechanics. [Online]. Available: https://saam.africa/

[27] B. Anwajler, "Potential of 3D Printing for Heat Exchanger Heat Transfer Optimization—Sustainability Perspective," *Inventions 2024, Vol. 9, Page 60*, vol. 9, no. 3, p. 60, May 2024, doi: 10.3390/INVENTIONS9030060.

[28] C. Y. Chien, T. N. Le, Z. H. Lin, and Y. L. Lo, "Numerical and experimental investigation into gas flow field and spattering phenomena in laser powder bed fusion processing of Inconel 718," *Mater Des*, vol. 210, p. 110107, Nov. 2021, doi: 10.1016/J.MATDES.2021.110107.

[29] "What is Computational Fluid Dynamics (CFD)? | Ansys." Accessed: Apr. 03, 2025. [Online]. Available: https://www.ansys.com/en-in/simulation-topics/what-is-computational-fluid-dynamics.

[30] T. M. Oyinloye and W. B. Yoon, "Application of Computational Fluid Dynamics (CFD) Simulation for the Effective Design of Food 3D Printing (A Review)," *Processes 2021, Vol. 9, Page 1867*, vol. 9, no. 11, p. 1867, Oct. 2021, doi: 10.3390/PR9111867.

[31] B.S. Surendra, K.S. Anantharaju, M. Rudresh, Mg-doped ZrO2 ceramic nanoparticles for thermal barrier coating and optical applications, Advanced Ceramic Coatings for Energy Applications, ELSEVIER SERIES IN ADVANCED CERAMIC MATERIALS, Feb-2024, ISBN: 978-0-323-99620-4. DOI: https://doi.org/10.1016/B978-0-323-99620-4.00020-8.

[32] Rudresh M, Nitesh Karbari, Maruthi BH, Investigation of Stresses in Turbine Engine Disc, International Journal of Advances in Scientific Research and Engineering, 3 (2017), 1-7. ISSN: 2454-8006, DOI: http://dx.doi.org/10.7324/IJASRE.2017.32478.