

Simulation of the Filling Dynamics in Ceramic Injection Molding

Yatin Darbar
School of Mechanical Engineering
University of Leeds
Leeds, United Kingdom
y.darbar@leeds.ac.uk

Roopika Ravikanna
School of Mechanical Engineering
University of Leeds
Leeds, United Kingdom
r.ravikanna@leeds.ac.uk

Mark Urch
Tarpey Harris
Morvern Group Ltd.
Denby, United Kingdom
mark.urch@tarpeyharris.com

Phil Lewis
Tarpey Harris
Morvern Group Ltd.
Denby, United Kingdom
phil.lewis@morverngroup.com

Krzysztof J. Kubiak
School of Mechanical Engineering
University of Leeds
Leeds, United Kingdom
k.kubiak@leeds.ac.uk

Zinedine Khatir
School of Mechanical Engineering
University of Leeds
Leeds, United Kingdom
z.khatir@leeds.ac.uk

Abstract—Ceramic Injection Molding (CIM) is a critical manufacturing route for producing complex ceramic components with tight dimensional tolerances, particularly in gas-turbine and aerospace applications. However, the process is governed by highly coupled multiphase, non-Newtonian, and non-isothermal phenomena, making defect-free mold filling difficult and costly to predict using experimental methods alone. In this work, a computational framework is developed to simulate and analyze the ceramic injection process. The approach is based on a modified Volume of Fluid formulation within an open-source finite-volume solver, incorporating a bespoke viscosity model dependent on local shear rate and temperature. The model resolves transient flow-front evolution, thermal coupling, and air displacement during mold filling. Validation is performed against published benchmark data and in-house short-shot experiments, demonstrating good agreement in terms of material-front shape and dynamic filling behavior. The validated model is applied to a representative ceramic core geometry to investigate injection filling dynamics and assess the influence of internal tie bars, which are commonly introduced for structural reasons but whose effects during injection are not well understood. A parametric study is conducted in which tie bar position is systematically varied. The resulting flow behavior is analyzed in terms of filling patterns, achievable fill fraction, and inlet pressure. The results show that tie bar placement has a minor impact on the achievable fill fraction but can reduce the pressure needed to fill the part by up to 36%. While certain configurations reduce peak inlet pressure requirements, they may also promote air entrapment and slightly reduce the maximum attainable fill. These findings highlight the trade-off between pressure reduction and defect risk and demonstrate the value of simulation-based analysis for supporting optimization of the ceramic injection molding process.

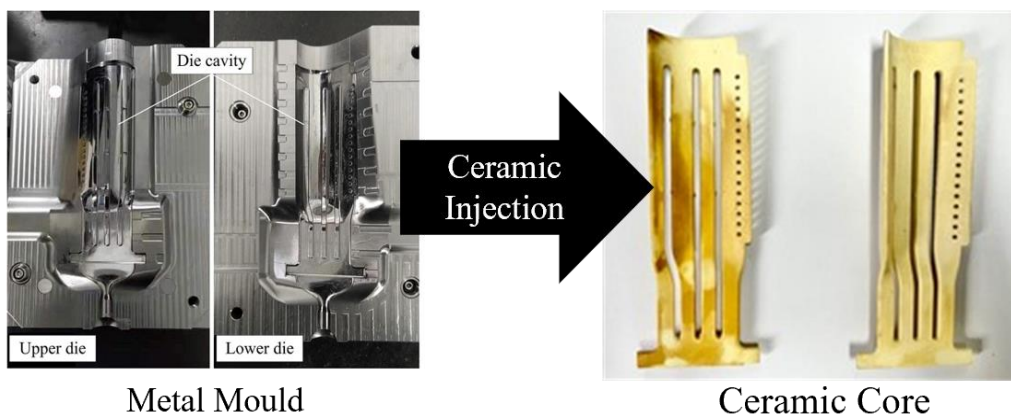
Keywords— *Computational Fluid Dynamics, Multiphase Flow, Non-Newtonian Rheology, Volume of Fluid, Injection Molding*

I. INTRODUCTION

Ceramic Injection Moulding (CIM) is a manufacturing process that enables the mass production of complex components with tight dimensional tolerances and excellent surface finish [1]. It has become a key manufacturing route in sectors such as aerospace, energy, electronics, and medical devices, where components frequently exhibit thin walls, internal channels, and intricate geometries [2–4].

In gas-turbine manufacture, CIM is widely used for producing ceramic cores that define the internal cooling passages of turbine blades and vanes. These cores must meet stringent geometric and structural requirements, as defects introduced during forming can propagate through downstream processes such as debinding, sintering, and investment casting, ultimately compromising component performance and yield [4–7].

Despite its industrial maturity, the CIM process remains challenging to control due to the complex rheological behaviour of ceramic feedstocks. The feedstock consists of a highly loaded suspension of ceramic powder within a polymer binder system, resulting in a material that exhibits strong non-Newtonian, shear-thinning behaviour and pronounced temperature dependence [8,9]. During injection, the flow is further complicated by multiphase effects,



Metal Mould

Ceramic Core

free-surface evolution, air displacement, and strong thermal coupling between the injected material and the mould walls. Defects such as incomplete filling, air entrapment, jetting, weld lines, and density inhomogeneities are frequently associated with the mould-filling stage, and are difficult to detect or rectify experimentally once formed [9,10]. Consequently, there is a strong industrial motivation to improve predictive capability during mould design and process parameter selection.

Computational modelling and simulation have therefore emerged as powerful tools for understanding and optimising injection moulding processes. Numerical methods based on Computational Fluid Dynamics (CFD) have been extensively applied to polymer injection moulding and, more recently, adapted for ceramic and powder injection moulding applications [12–14]. These approaches enable detailed analysis of flow-front evolution, pressure development, temperature distribution, and potential defect formation mechanisms within complex geometries.

However, accurately simulating CIM remains challenging. Many commercial tools rely on simplified geometrical assumptions or reduced-order formulations, which may be insufficient for capturing three-dimensional mould filling, complex internal features, and strongly coupled multiphysics behaviour [8]. Furthermore, reliable material characterisation data for ceramic feedstocks are often limited, and bespoke rheological and thermal models are required to represent industrial feedstocks with sufficient fidelity [16].

Internal geometric features, such as tie bars, are commonly introduced into ceramic core designs to enhance structural rigidity and reduce warpage during downstream thermal processing. While their mechanical function is well understood, their influence on injection mould filling behaviour has received limited attention in the literature. Such features locally modify flow pathways, shear rates, and air evacuation routes, and can therefore influence both the pressure required for filling and the likelihood of defect formation [6,17].

In this work, a multi-physics simulation framework is developed to investigate the ceramic injection moulding process in geometries representative of industrial ceramic cores. The approach resolves transient, non-Newtonian, multiphase, and non-isothermal flow behaviour using a Volume of Fluid formulation and a bespoke viscosity model implemented within an open-source CFD solver. Following validation against published and in-house experimental data, the model is applied to analyse mould-filling dynamics and to assess the influence of tie bar position on filling behaviour, achievable fill fraction, and inlet pressure requirements. The results aim to support informed design and optimisation of CIM processes for complex industrial components.

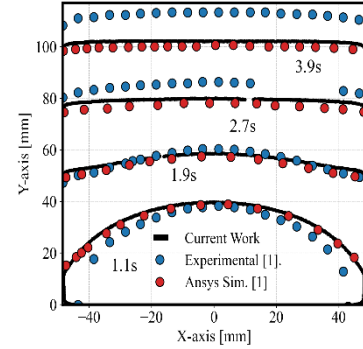
II. METHODOLOGY

The open source CFD software OpenFOAM is used to create a simulation framework capable of modelling the ceramic injection molding process. This consists of a Volume of Fluid

(VOF) Method for modelling multiphase flow with a bespoke rheology model to capture the shear thinning and temperature-dependent nature of the ceramic material.

A. Governing Equations

The ceramic injection process is modelled as transient, incompressible, laminar flow [15]. The governing equations consist of the conservation of mass, momentum and energy solved within a finite-volume framework. To capture the mould filling process, a Volume of Fluid (VOF) formulation is employed to track the interface between the ceramic feedstock and the displaced air phase. A scalar phase fraction field is solved to determine material distribution within the computational domain, enabling transient prediction of the



advancing flow front. This method results in single *compressible* Navier-Stokes for a mixture fluid, therefore the conservation of mass is given by

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0,$$

where $\mathbf{u}$ and ρ denote the mixture fluid velocity and density. The conservation of momentum reads

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{1}{\rho} \nabla p + \nabla \cdot (\mu \nabla \mathbf{u}) + \mathbf{f},$$

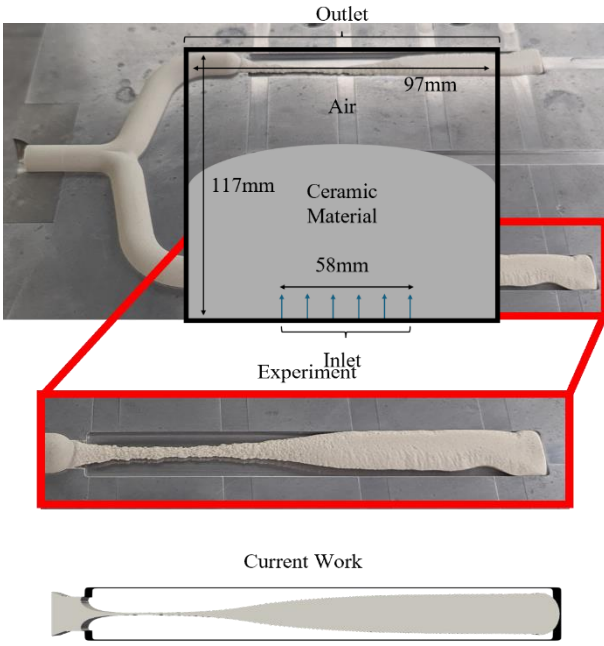
where p , ρ and μ are the mixture fluid pressure, density and viscosity respectively with $\mathbf{f}$ representing the body forces. Thermal effects are captured through the conservation of energy

$$\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T = \nabla \cdot (D \nabla T) + \Phi,$$

where T is temperature, D is the thermal diffusivity and Φ represents viscous dissipation. The coupling between the flow of the ceramic and its temperature arises through the temperature and shear rate dependent viscosity described in Section II.C.

B. Ceramic Rheology

The ceramic feedstock is modelled as a homogenous, non-Newtonian fluid. The viscosity of the ceramic is defined through a bespoke rheology model developed for this study from in-house experimental measurements. Here the viscosity is expressed as both a function of local shear rate and temperature



$$\mu(\dot{\gamma}, T) = A_1 e^{A_2 T} \dot{\gamma}^{A_3 T + A_4}$$

where $\dot{\gamma}$ is the second invariant of the shear rate tensor. This formulation enables the model to capture the strong sensitivity of the flow to local deformation and thermal conditions. Thermal coupling is critical in the injection process, as temperature variations significantly influence viscosity and therefore mold filling behavior. By resolving the energy equation simultaneously with momentum transport, the approach accounts for feedback between viscous heating, heat transfer to the mold walls, and evolving flow dynamics.

C. Boundary & Initial Conditions

Fig shows a model of the computational domain used in this study. As prescribed plug velocity boundary condition is imposed at the injection inlet to represent the material inflow. The magnitude of the inlet velocity is selected to achieve a uniform flow rate as used in the injection process.

A custom venting boundary condition is implemented to allow evacuation of the air phase while preventing the ceramic feedstock from exiting the domain. This boundary condition enables realistic modelling of venting channels put into metal molds without having to directly mesh submillimeter sized channels.

All mold walls are treated as stationary with no-slip. A constant ambient wall temperature of 25°C is imposed to represent the thermal control of the mold. The inject ceramic material enters the domain at a specified maximum temperature, the value of which is omitted due to confidentiality constraints.

III. VALIDATION

Validation of the proposed simulation method is conducted through comparison with both published benchmark data and inhouse experimental observations,

assessing the models ability to reproduce flow-front evolution during mold filling.

A. Previous Work

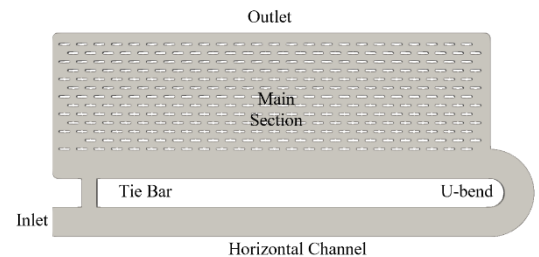
The numerical results are first validated against the experimental and numerical study of Mukras and Al-Mufadi [5]. The simulation domain, shown in the left panel of Figure 2, consists of a rectangular cavity measuring $97\text{ mm} \times 117\text{ mm}$, with a centrally positioned inlet of width 58 mm located along the bottom edge of the mould. The upper boundary of the cavity is modelled as an outlet to permit venting of displaced air during the filling process, consistent with the reference study.

The right panel of Figure 2 compares the predicted material-front positions at four representative time instances (1.1 ms , 1.9 ms , 2.7 ms , and 3.9 ms). The black contour denotes the flow-front evolution predicted by the simulation framework developed in this work, while the blue and red markers correspond to the experimental and numerical results reported by Mukras and Al-Mufadi [5], respectively. Good agreement is observed across all time instances, demonstrating the model's ability to capture both the overall filling pattern and the transient progression of the material front.

B. In-house Short Shot Experiments

Further validation is provided through in-house experimental testing, the results of which are presented in Figure 3. A controlled short-shot experiment was performed by deliberately under-filling a rectangular mould, enabling direct visual comparison between the experimentally observed material-front shape and the corresponding simulation predictions.

The simulation accurately reproduces the characteristic jetting behaviour of the ceramic feedstock as it enters the cavity. Upon injection, a focused jet forms and propagates across the mould before impinging on the opposite wall and spreading to coat adjacent surfaces. When injection is halted, the material retains sufficient inertia for the bulk flow to continue advancing transiently. During this phase, and in the absence of further inflow, the jet progressively thins and undergoes necking as viscous resistance becomes dominant. This transient behavior, governed by the interplay between inertial and viscous forces, is captured well by the numerical model. The close qualitative agreement between simulated



and experimental flow-front evolution provides confidence in the capability of the developed methodology to predict complex filling dynamics encountered in ceramic injection molding.

IV. RESULTS

A. Problem Description

The ceramic injection process is investigated using a simple but representative core geometry inspired by industrial turbine applications. The geometry consists of a horizontal inlet channel, a U-bend and a main section that contains periodic oval features. The geometry also contains an internal connecting channel called a tie bar. Tie bars are commonly incorporated in the ceramic core designs to improve structural integrity and reduce warpage during downstream processing of the core once injection is complete. However, their influence on material flow during the injection process is not currently understood.

To address this, a series of transient simulations were conducted to examine mold filling behavior, identify potential defect mechanisms and quantify the effect of tie bar position on process performance. All simulations employed the validated modelling framework described in Section using the geometry shown in Figure.

B. Filling Dynamics

The predicted filling dynamics reveal a highly transient, non-uniform flow behavior dominated by inertial effects at early time and viscous resistance as filling progresses.

As shown in Figure X the feedstock enters the horizontal channel and negotiates the U-bend before advancing through the main section around the periodic features. The tie bar acts to divert the main flow from the horizontal channel into the main section creating two main flow fronts of the ceramic material. The material jets through the tie bar channel into the main section creating two areas of flow separation from the mold walls and therefore two air pockets are formed either side of downstream side of the tie bar. The advancing flow fronts from the tie bar and the U-bend then meet along the base of the main section forming a knit line (Figure X - 0.4s) at the mid-right side of the main section. The interaction of two meeting mold fronts can create points of weakness as air may not be able to escape and allow the material to merge naturally. The simulation method predicts this with a small amount of air being trapped in the region where the flow fronts meet. During later stages of filling the combined flow front progresses vertically through the main section of the

part indicating venting must be placed along the whole top edge section rather than in localized positions.

C. Effect of Tie Bar Position on Filling Behaviour

To quantify the influence of tie bar placement, simulations were performed for varying tie bar placements along the span of the horizontal channel. Table I presents the tie bar positions investigated.

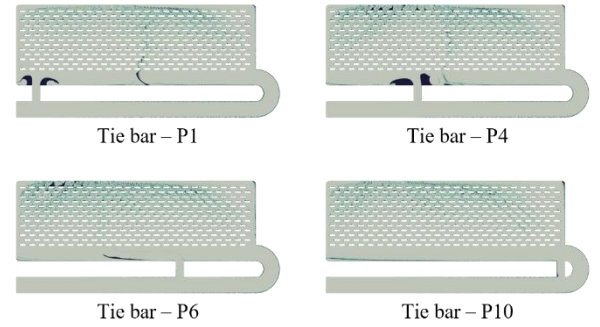
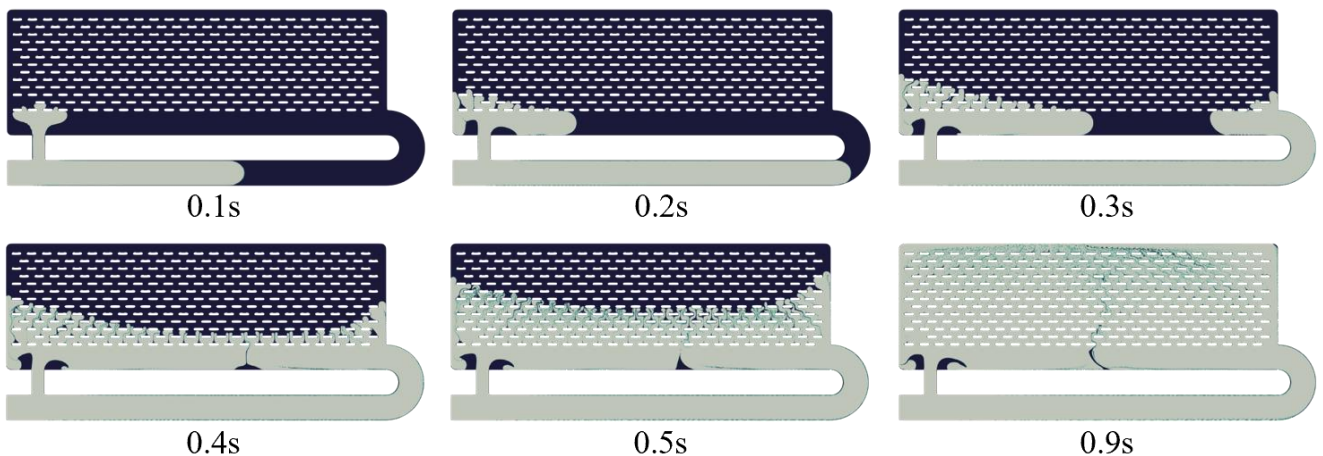


Figure X compares the final composition of the ceramic material after injection for four tie bar positions (P1, P3, P6, P10) investigated. The results show that the tie bar position has a distinct qualitative effect on the filling during injection. A nonlinear trend of first increasing the size of the separation zone and then complete irradiation of it as the tie bar is moved horizontal shows there is a non-trivial interaction between the two flow fronts.

To quantify the effect of varying the tie bar position the fill fraction and the inlet pressure were analyzed at 0.9s for all tie bar configurations. Figure X presents the final fill fraction and inlet pressure as a function of tie bar position. Included on these figures is also the case in which no tie bar is present in the geometry (indicated by a dashed red line).

In all cases the presence of a tie bar slightly reduces the maximum achieved fill fraction compared to a configuration without a tiebar. This reduction is linked to the separation and meeting flow fronts that are induced by the presence of a tie bar. However the maximum difference in underfilling as compared to no tie bar case is less than 1%. The results also indicate the presence of a tie bar can significantly reduce the



inlet pressure required to achieve mold filling. Across all tie bar placements simulated the reduction of pressure was between 4% - 36%. The reduction is attributed to redistribution of flow pathways where the tie bar allows material to avoid having to be injected through the whole main section from right to left. An optimal tie bar position must balance the competing objectives of minimizing injection pressure while avoiding adverse filling partners and

Configuration Name	Tie Bar Centre Position [mm]
P1	12.5
P2	27.5
P3	42.5
P4	57.5
P5	72.5
P6	87.5
P7	102.5
P8	117.5
P9	132.5
P10	147.5

defect formation. As fill fraction goes down there is an increased risk to defect formation. As inlet pressure decreases there is less wear on equipment which is commercially favorable.

V. CONCLUSION

This study presents a computational investigation of the ceramic injection molding process, with particular emphasis on understanding filling dynamics and assessing the influence of internal tie bars on process performance. A validated multi-physics simulation framework was applied to a representative ceramic core geometry relevant to industrial gas-turbine manufacture.

The results demonstrate that mold filling is governed by strongly transient jetting, flow separation, and free-surface effects. The simulations highlight how potential defects arise in ceramic cores, through understanding the filling dynamics of the injection process.

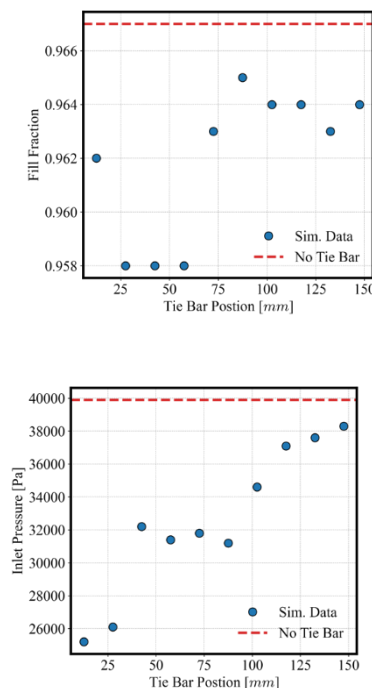
A parametric study was undertaken to investigate the effect of tie bar position on mold filling behavior. The presence and

placement of tie bars were shown to have an impact on both the achievable fill fraction and inlet pressure response. While tie bars can significantly reduce the peak inlet pressure required for filling, which indicates a potential benefit in terms of reduced equipment loading and wear, they also introduce flow obstructions that may promote air entrapment and slightly reduce the maximum attainable fill. These competing effects underline the need for careful tie bar placement during component design.

Overall, the findings demonstrate that internal geometric features such as tie bars play a dual role during injection, influencing both hydraulic resistance and defect risk. The results highlight the value of simulation-based analysis for identifying optimal design configurations and supporting informed optimization of ceramic injection molding processes. Future work will focus on extending the parameter space explored and integrating systematic optimization strategies to further improve process robustness and part quality.

REFERENCES

- [1] Chauhan, A.S., Anirudh, B., Satyanarayana, A. and Rallapalli, P., 2020. FEA optimization of injection parameters in ceramic core development for investment casting of a gas turbine blade. *Materials Today: Proceedings*, 26, pp.2190-2199.
- [2] Stanimirović, Z. and Stanimirović, I., 2012. Ceramic injection molding. *Some Critical Issues for Injection Molding*, pp.131-148.
- [3] Tosello, G., Marhöfer, D.M., Islam, A., Müller, T., Plewa, K. and Piötter, V., 2019. Comprehensive characterization and material modeling for ceramic injection molding simulation performance validations. *The International Journal of Advanced Manufacturing Technology*, 102(1), pp.225-240.
- [4] Pradyumna, R. and Baig, M.A.H., 2012. Ceramic cores for turbine blades: a tooling perspective. *Int J Mech Ind Eng*, 2(4), pp.1-7.
- [5] Cademartori, S., Humphreys, N., Gebelin, J.C. and Brooks, J., 2018, January. Implementing CFD Modelling to Address Defect Formation in Core Injection Moulding. In *TMS Annual Meeting & Exhibition* (pp. 213-222). Cham: Springer International Publishing.
- [6] Gromada, M., Świeca, A., Kostecki, M., Olszyna, A. and Cygan, R., 2015. Ceramic cores for turbine blades via injection moulding. *Journal of Materials Processing Technology*, 220, pp.107-112.
- [7] Pabst, W., Havrda, J. and Gregorova, E., 1999. Rheology of ceramic injection-molding feedstocks. *Ceramics-Silikaty*, 43(1), pp.1-11.
- [8] Drummer, D. and Messingschlager, S., 2014, May. Ceramic injection molding material analysis, modeling and injection molding simulation. In *AIP Conference Proceedings* (Vol. 1593, No. 1, pp. 582-586). American Institute of Physics.
- [9] Nastac, L., Zhang, L., Thomas, B.G., Sabau, A., El-Kaddah, N., Powell, A.C. and Combeau, H. eds., 2012. *CFD Modeling and Simulation in Materials Processing*. John Wiley & Sons.
- [10] Baum, M., Anders, D. and Reinicke, T., 2023. Approaches for numerical modeling and simulation of the filling phase in injection molding: A Review. *Polymers*, 15(21), p.4220.
- [11] Mukras, S.M. and Al-Mufadi, F.A., 2016. Simulation of HDPE mold filling in the injection molding process with comparison to experiments. *Arabian Journal for Science and Engineering*, 41(5), pp.1847-1856.
- [12] Park, S.J., Ahn, S., Kang, T.G., Chung, S.T., Kwon, Y.S., Chung, S.H., Kim, S.G., Kim, S., Atre, S.V., Lee, S. and German, R.M., 2010. A review of computer simulations in powder injection molding. *Int J Powder Metall*, 46, pp.37-46.
- [13] Baum, M., Jasser, F., Stricker, M., Anders, D. and Lake, S., 2022. Numerical simulation of the mold filling process and its experimental validation. *The International Journal of Advanced Manufacturing Technology*, 120(5), pp.3065-3076.
- [14] Easley, M.L. and Smyth, J.R., 1996. *Ceramic gas turbine technology development* (Vol. 78736, p. V002T04A006). American Society of Mechanical Engineers.



- [15] Pedro, J., Ramôa, B., Nóbrega, J.M. and Fernandes, C., 2020. Verification and validation of openInjMoldSim, an open-source solver to model the filling stage of thermoplastic injection molding. *Fluids*, 5(2), p.84.
- [16] Easley, M.L. and Smyth, J.R., 1996. *Ceramic gas turbine technology development* (Vol. 78736, p. V002T04A006). American Society of Mechanical Engineers