SIMULATION-BASED OPTIMISATION FOR THE SIDE SEAM HEATING NOZZLES IN THE PAPER CUP MANUFACTURING SYSTEM

Lappeenranta–Lahti University of Technology LUT

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ABSTRACT

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Simulation-based optimisation for the side seam heating nozzles in the paper cup manufacturing system

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This thesis investigates the influence of hot-air nozzle geometry on the paper cup side seam heating stage during the manufacturing process, this is a critical step which shapes the seal quality, energy efficiency and the overall production consistency. Although the sealing period is brief, it requires carefully controlled heating to properly activate the polymer coating on the paperboard. Four nozzle configurations were modelled in Autodesk Fusion 360 and evaluated using Computational Fluid Dynamics simulations in Ansys Fluent. The baseline model which is based on the NEW TOP-138S paper cup manufacturing machine at LUT packaging laboratory, showed strong but non-uniform heating, creating distinct hot spots under the impinging jets and cooler regions between the jets. Three modified configurations, a slotted outlet, a multi-row arrangement with smaller jets, and an enlarged-outlet variant, were modelled to explore alternative effects. Among these, the multi-row small-outlet design produced the most uniform and efficient heat distribution, achieving higher average temperatures with minimal variation across the side seam. The findings highlight how relatively small geometric changes can improve both thermal performance and sealing reliability, and they offer a clear direction for future optimisation of industrial cup-forming equipment.

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Espoo, November 2025

Abdul Malik

SYMBOLS AND ABBREVIATIONS

Roman characters

c_p	Specific heat capacity	J/kg·K
T	temperature	°C

Greek characters

ρ	Density	kg/m³
κ	Thermal conductivity	W/m·K

List of Abbreviations

CAD	Computer-aided design
CFD	Computational fluid dynamics
KE	Kinetic Energy
PE	Polyethylene
PLA	Polylactic Acid
UI	Uniformity Index

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DECLARATIONS

Turnitin

The originality of this thesis has been reviewed with the Turnitin similarity checking service.

AI usage

The author of the thesis, Abdul Malik used the following AI-tools during the preparation of the thesis:

1. ChatGPT
    a. Purpose of use: Troubleshooting CFD simulation.
    b. Explanation of the use of the tool: The tool was used to identify input issues by providing error codes during simulation
2. Grammarly
    a. Purpose of use: Proofread
    b. Explanation of the use of the tool: It was used to check and correct grammar, spellings and punctuation.

Responsibility

The author, Abdul Malik, takes full responsibility for the content of this thesis and has reviewed and edited the content generated by the possible use of AI tools.

1 Introduction

In today's world, there is increasing demand for sustainable packaging material which can replace traditional packaging material such as plastics, which has led to increase paper-based products, such as the paper cup which is used as an alternative for plastic cups. Prominently, paper cups are being widely used in the food and beverages sector. The manufacturing process for the paper cup is highly specialised and technically demanding, one key stage among several stages is heating of side seam of the paper cup, this step is essential in order to prepare the polymer-coated paperboard for sealing and forming. During the heating step the coating gets softened, typically, the coating is polyethylene (PE) or for bio-based coatings, polylactic acid (PLA) is also used, to ensure proper bonding during the cup assembly (Triantafillopoulos et al., 2020).

Despite heating being a key step in the cup manufacturing process, there is very negligible research attention given to heating nozzles. These hot air nozzles are used to preheat specific sections of the cup blank before forming. The traditional designs often can result in non-uniform heat distribution, which can weaken the seal, it can distort material, and cause defects such as side seam separation and bottom leakage. These defects can cause increase in rejection rates and wastage of energy, causing the overall efficiency of the production to decrease.

In a broader context, sustainable manufacturing, optimal thermal process in paper cup manufacturing, holds both economic importance as well as environmental importance. By refining the heating stage through computational modelling, it becomes possible to reduce energy utilization, minimise thermal degradation of paperboard, and enhance seal reliability all without requiring extensive and expensive physical prototyping. The application of Computational fluid dynamics (CFD) in this thesis allows for deep analysis of airflow, temperature gradients, and heat transfer behaviour of nozzle and across the paper surface. This thesis investigates the performance of existing side seam hot air nozzle, based on the findings of thermal efficiency, material response and process efficiency, this thesis aims to determine whether a redesign of the heating nozzle is required. If the research indicates that the existing nozzle configuration are suboptimal, then an optimised nozzle design will be proposed to improve heat distribution and forming quality.

1.1 Objective and research question

The objective of the thesis is to evaluate the current performance of the existing nozzle used in the paper cup forming process. It focuses on heat distribution analysis, and process efficiency during the sidewall heating stages. The research aims to find limitations within the nozzle design that can lead to defects. Based on the findings, if the configuration is suboptimal, then an optimised nozzle design will be proposed to achieve uniform heating and improved forming quality.

The main research questions of the thesis are

1. Can the side heating be optimised in the cup manufacturing system for enhanced energy efficiency and heat distribution by nozzle design?
2. How can nozzle design in a cup manufacturing system be optimised to improve heat distribution and energy efficiency?

The sub-questions are

1. How does the current nozzle perform in terms of temperature uniformity?
2. What are the effects of varying nozzle geometry?
3. What improvements, if any, can be made to the nozzle for better performance?

1.2 Scope and limitations

This thesis focuses on the optimisation of side seam heating in the paper cup manufacturing process, with an emphasis on the nozzle geometry and the thermal efficiency. The thesis addresses the following key areas.

1. The thesis investigates the existing nozzle setup used in the NEW TOP-138S paper cup manufacturing machine at LUT packaging laboratory, used in the side seam heating during cup forming.
2. Investigation of the relationship between the nozzle geometry, placement, and the airflow parameters on the heating performance.
3. Development of CAD models in Autodesk Fusion 360 for redesigned nozzle model concepts with increased thermal efficiency.

4. Simulations of the proposed designs using CFD in Ansys Fluent and analysing the thermal efficiency.
5. Proposal of an optimised nozzle configuration that enhances heating uniformity, reducing defects, and improving overall production efficiency

The thesis is subjected to several limitations that define the boundaries of the research.

1. The thesis is simulation and design-oriented, no physical prototypes or industrial-scale testing of the optimised nozzle design will be carried out within the thesis.
2. The analysis relies on supplier data, literature sources, and industrial references for material and process parameters.
3. The scope is restricted to hot air systems applies in the paper cup sealing process, other sealing methods such as ultrasonic or other techniques are not tested.
4. The proposed nozzle configuration is developed with reference to the “NEW TOP-138S (New Debao Machinery)” cup forming machine and may require adaptation for other machine types or product geometries.

1.3 Methodology

This thesis utilizes a design and simulation-based methodology to optimise heating nozzles of the paper cup side seam. The thesis starts with literature and data review, followed by CAD modelling in Autodesk Fusion 360 of nozzle designs. Next, CFD in Ansys Fluent, simulations are used to look at how hot air flows around in different geometries and placements. These results are then compared to the baseline performance to suggest a better nozzle design that will ensure uniform heating, energy efficiency, and practical and financial feasibility for integration into the NEW TOP-138S machine. The simulated results are post-processed to obtain key quantitative indicators such as average surface temperature, temperature uniformity at the side seam paper. Comparative analysis of all the models against the baseline design is used to identify configurations that achieve improved heat uniformity and reduced energy losses.

2 Literature review

The literature review of the thesis starts with an overview of the cup manufacturing system, discussing the various stages in the process, then different sealing techniques will be explored, like hot air sealing and ultrasonic sealing. After the sealing section, the thesis will look into the nozzle design, then the defects caused due to heating and forming will be explored, and finally, the CFD section will be looked into.

2.1 Cup manufacturing process

The paper cup forming process is very specialised process, it combines precise material preparation, automatic forming and quality control to manufacture a safe, leakproof and consistent paper cup. It begins with preparation of the raw materials 'paper cup blank' shown in Figure 1 (a), are die-cut from PE coated paperboard with a total grammage of 150–350 g/m². Similarly, circular bottom pieces shown in Figure 1 (b), are punched directly from a continuous paperboard reel during the manufacturing process

(a) (b)

Figure 1. (a) Paper cup blank (b) bottom piece (LUT packaging laboratory).

During the forming stage, the paperboard blanks is wrapped into cup and then sealed along the side seam using heat. Heating can be done using various techniques such as hot air, ultrasonic. Then the sealed cup moves to bottom feeding section, where a circular punched piece is inserted. After which bottom curling takes place. During this stage, the lower edge of the cup wall is curled around the bottom blank to position it for sealing. This is then followed by bottom knurling, where heat and pressure fuse the PE coating and create the knurled grooves that secure the bottom piece. The next step is top curling, during this stage the rim of the paper cup is curled into a smooth, rolled edge, which increases the rigidity of the cup and also makes the cup comfortable to drink out of.

The cup forming process stages, shown in Figure 2.

1. Paper cup blank- A paper cup blank is blanked out of paperboard roll. These are wedge-shaped blanks which will form the cup's side wall.
2. Sealing- The paper cup blank is rolled into a cylindrical shape, and the sides are sealed together using heat making a cylindrical cup.
3. Bottom feeding- The bottom piece is blanked out of roll then it is placed at the bottom opening of the cup to form the base.
4. Bottom curling – The lower edge of the cup body is curled inward to prepare it for joining with the bottom disc, ensuring proper fit and preventing leakage.
5. Bottom knurling- The bottom edge is knurled around the base to ensure it is tightly sealed.
6. Top curling- The upper rim of the cup is curled outward to provide the paper cup with strength and prevent sharp edges.
7. Ready cup- The paper cup is ready, fully formed, and ready for use

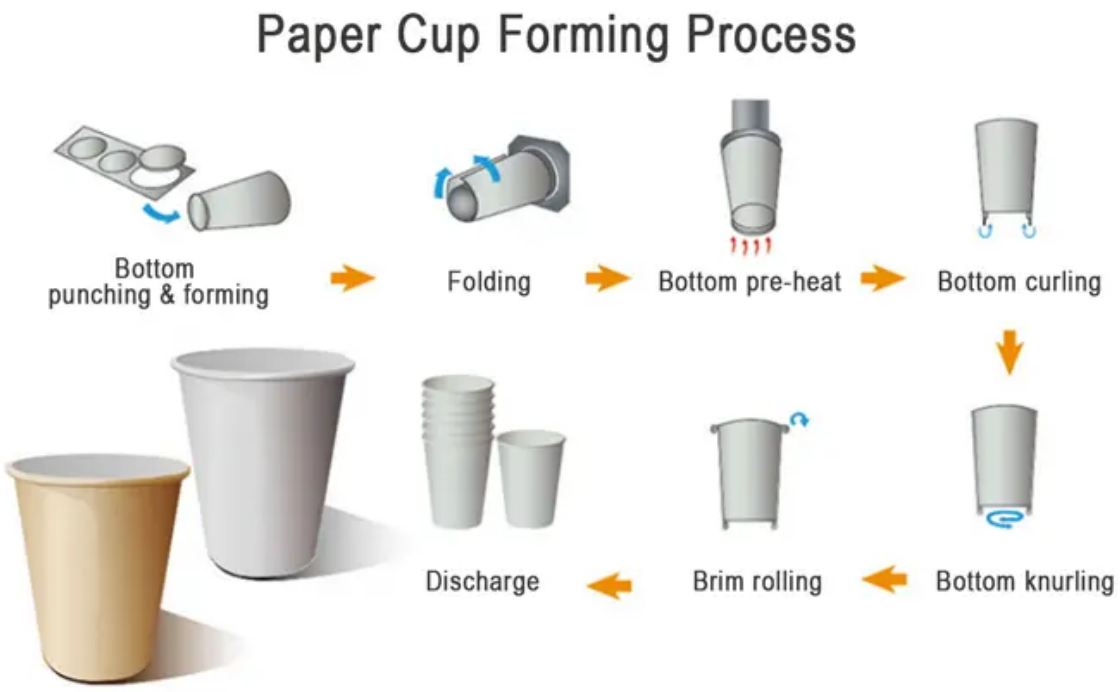

Figure 2. Paper cup manufacturing stages (NewTop, 2024).

Shown in Figure 3 is the NEWTOP-138S paper cup manufacturing machine, which is a high-speed, intelligent production machine used in paper cup manufacturing. According to the manufacturer, the machine features a desktop configuration that isolates the forming units from transmission components, enabling enhanced reliability and simplified maintenance. It supports cup sizing from 2.5 oz to 16 oz and is capable of producing 140 cups per minute under optimal conditions. The machine is equipped with PLC (Programmable Logic Controller) control system, photoelectric sensors, and CCD (Charge-Coupled Device) inspection, the machine ensures high yield rates and has an integrated quality monitoring system. In the context of this thesis, the simulation design and nozzle optimisation are developed in alignment with this machine's layout. (Zhejiang New Debao Machine, 2025).

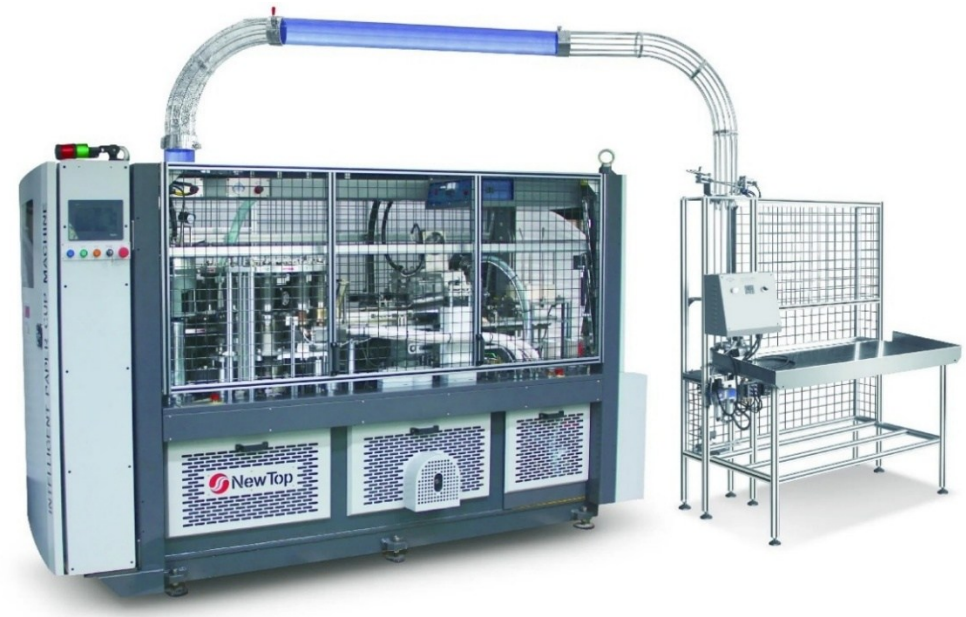

Figure 3. Cup manufacturing machine (Zhejiang New Debao Machine, 2025).

Automation plays a major role in modern paper cup manufacturing systems. The entire sequence from feeding the paperboard to ejecting the finished cups are controlled by servo-driven mechanisms and temperature regulated stations. These systems provide synchronisation between cutting, forming, heating, and the curling processes, maintaining consistent quality. Some paper cup manufacturing machines are capable of producing 300 cups per minute (Hörauf, 2024), that is, 5 cups made every second. Each stage of production requires careful monitoring of temperature, air pressure and timing parameters to prevent defects such as incomplete seals, wrinkling, or delamination. One of the sensitive operations among all operations is sealing of the paper cup side seam, here, hot air must soften the polymer coating uniformly across the side seam width. If the temperature or airflow distribution is non-uniform, it can result in weak bonding or overheating of the paper substrate, compromising both seal strength and visual appearance.

2.2 Side seam heating

Side seam heating is one of the most critical stages in the paper cup forming process, as it prepares the overlapping edges of the paperboard for sealing. In this step, a stream of heated air softens the polymer coating commonly PE or, for bio-based alternatives, PLA, before the edges are pressed together to create a strong, leak-resistant seam. The consistency of this heating process influences directly the strength and durability of the finished paper cup.

Several factors affect the quality of the paper cup side seam, such as the shape of the nozzle, the airflow rate, the temperature, and the dwell time it is exposed to. If heat isn't uniform or strong enough, weak bonding or leaks can happen. On the other hand, too much heat can hurt the paperboard fibers or the coating, which can cause number of surface defects or waste energy (Ilhan et al., 2021). Furthermore, the way the paperboard reacts to heat can change depending how thick the paperboard is, uniformity of coating, or the humidity in the air. This makes process control and parameter tuning very critical, especially in high-speed production where some machines are capable of making 300 cups per minute, even small changes can cause quality problems.

Recent changes to the nozzle design, such as adjustable angles and multi-port outlets, have made airflow more stable and effective. Airflow and heat distribution are now increasingly being modelled by CFD tools. This helps manufacturers adjust the placements of nozzles and heating parameters to improve sealing performance and energy efficiency (Morris, 2021). The move toward sustainable coatings that can be recycled or composted has also made it more critical to be able to control the temperature very precisely, since bio-based materials usually have narrower processing windows and are more likely to overheat (Tyagi et al., 2021).

Side seam heating is very critical step, but it hasn't been researched as much when compared to other steps such as bottom sealing or knurling. More focused research is needed to improve nozzle configurations, lower defect rates, and help the switch to eco-friendly coatings without hurting the quality or speed of making paper cups.

2.3 Side seam sealing

Heat sealing for a long time has been the predominant way to make fiber-based containers like paper cups that hold liquids. The idea is to use heat and pressure to activate a thermoplastic coating, usually PE or newer bio-based polymers like PLA, to stick two surfaces together. The effectiveness of heat seals depends a lot on the temperature, dwell time, and pressure, as well as the type of polymer, the thickness of the coating, and the surface morphology. Insufficient regulation of these parameters results in incomplete fusion, suboptimal adhesion, and the development of leaks. Even small changes in the crystallinity of the polymer and the formulation of the coating could change the temperature at which the seal starts and the strength of the fiber tear (Kanani Aghkand, 2021). Shown in Figure 4 is a paper cup being sealed.

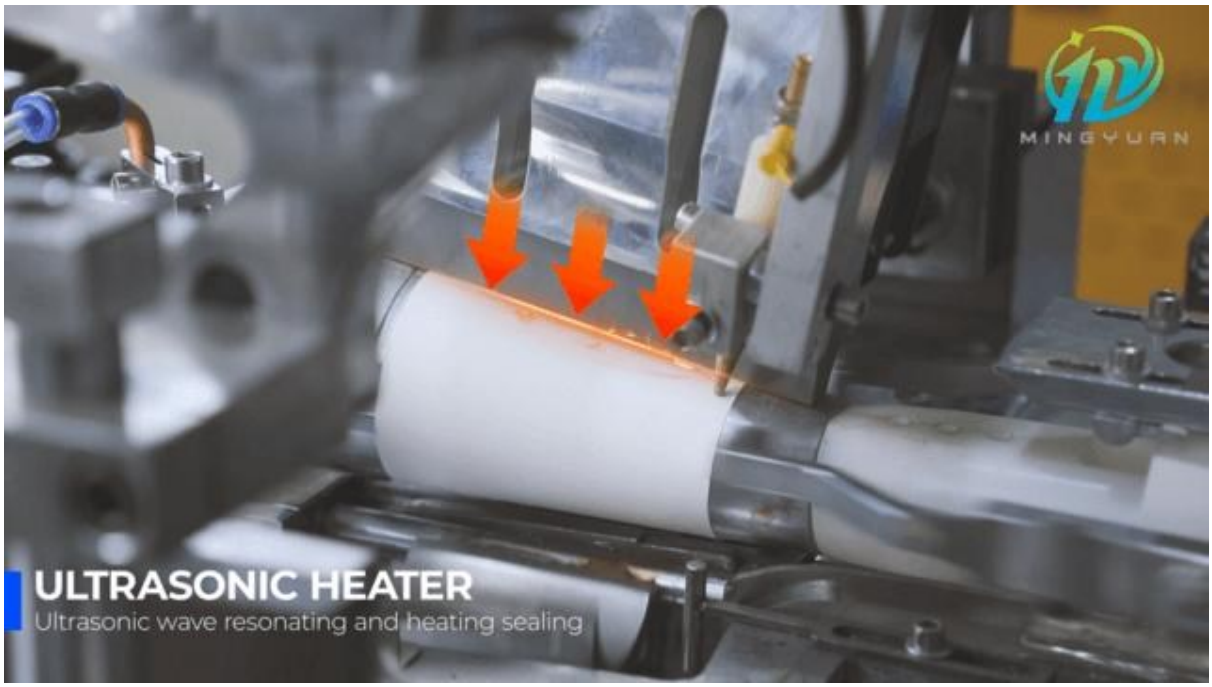

Figure 4. Ultrasonic heating (Mingyuan paper cup machinery, 2024).

Hot air sealing

Hot air sealing is a common method used in fiber-based packaging. It works by blowing pre-heated air onto the polymer coating to soften it before the material is compressed to make a seal. This method is better than hot bar sealing because it keeps the heated jaws from touching the material directly, which reduces mechanical wear and allows for more flexible machine setups. However, airflow temperature, nozzle positioning and dwell time, these sealing parameters significantly command its efficiency, if they are not properly set, the interfaces might become weak, and the polymer may not completely fuse (Tiitola, 2021). Due to susceptibility of paperboard to moisture, heat sealing becomes complex because humidity changes the fiber size and coating properties, making seals less reliable (Tiitola, 2021). The susceptibility of paperboard to moisture makes heat sealing complex because humidity changes the size of the fibers and the properties of the coating, which makes seals less reliable (Tiitola, 2021). Hot air sealing is robust and is being extensively used in the industry, but it uses a lot of energy and is sensitive to the environment, which are still big problems.

Ultrasonic sealing

Ultrasonic sealing is an advanced method used to make robust seals in paper-based packaging without the application of external heat. A transducer makes high-frequency mechanical vibrations, usually between 20 and 40 kHz, which are then sent to the sealing zone through a sonotrode. The vibrations create localized frictional heat at the interface of the materials, which heats and softens the thermoplastic coating layer (PE or PLA) on the paperboard. When the vibration caused by the transducer stops, the molten layer becomes hardened when it cools, and pressure is applied for a short time, making a strong seal. This method is faster and uses less energy when compared to traditional heat sealing. As this process uses less energy, it makes a eco-friendly alternative to traditional sealing methods to produce paper cups and cartons (Mohamed,2024). Ultrasonic sealing offers environmental advantages by lowering the risk of scorching, allowing sealing through light contamination, and using less energy. Recent improvements have made it possible to seal uncoated paper materials, which makes them even more useful in eco-friendly packaging systems. This development shows the capacity of the ultrasonic sealing process to replace traditional methods while ensuring good seals and enhancing process efficiency (Herrmann Ultrasonics, 2023).

2.4 Paperboard properties

Paperboard is a fiber-based packaging material that is being increasingly used in the food, drink, and consumer goods industry. Paperboard is strong, can be printed on, and also mainly sustainable. It is used for folding cartons and liquid packaging because its multi-layered fiber structure makes it stiff and keeps its shape. The grammage usually falls between 160 and 500 g/m² (Prontopack, 2022), depending on what it will be used for.

From a mechanical point of view, paperboard is stiff, strong in tension, and resistant to compression, these properties are important for withstanding stress during storage, handling, and transportation. The direction of fibers commands the properties of paperboard, which causes anisotropy, where the mechanical behaviour is different along the machine and cross-machine directions. Protection of products and branding is also easier as the smooth surface makes it easier for printing and coating to stick on to (Alava et al., 2006). Shown in Figure 5 are the different layers of the cup stock.

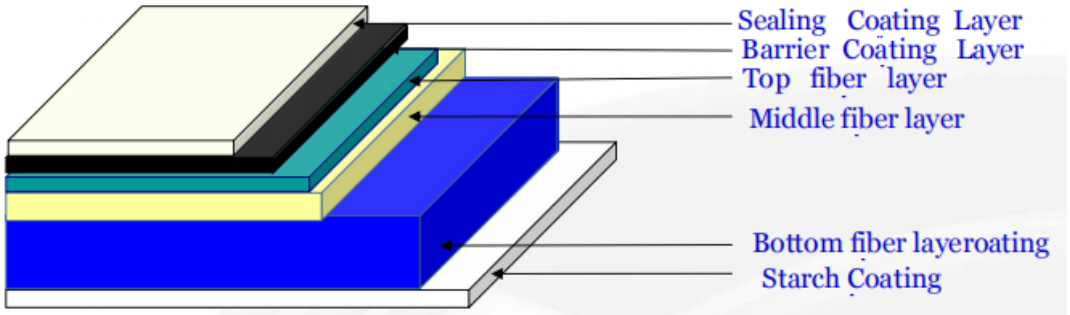

Figure 5. Cup stock layers (Sure-Paper, 2024).

When it comes to barrier properties, paperboard alone has very low resistance to grease, moisture, and oxygen. To enhance the barrier properties, paperboard is often coated with functional materials like PE, biopolymers like PLA, or thin layers of aluminium. These coatings make the paperboard useful in places where it needs longer shelf life or enhanced protection. Paperboard is made from renewable fibers, which can be recycled, making it a good choice for sustainable packaging solutions (Licciardello, 2017)

Figure 5 shows that the food grade paperboard used in the paper cup manufacturing is often made of several layers, these layers are specifically designed to provide with strength, barrier protection, and to increase sealing performance. The core is made of up of many layers, bulk and stiffness to the core is given by the middle layer, while the top and bottom layers improve surface quality and improve printability. To improve performance functional coatings can be used. For example, starch-based coating improves bonding and the print surface, for protection against grease, and oxygen barrier coating can be used, and a sealing coating makes sure that the heat or ultrasonic sealing processes work with the material. Also, one coat can work both as a barrier and a seal. Because of these layers, the paperboard material is able to keep its mechanical strength while also ensuring food safety standards are met and the barriers are sustainable cup packaging uses (Sure-Paper, 2024).

2.5 Nozzle design

Hot air nozzles play a crucial role in paper cup side seam sealing, by delivering a concentrated stream of hot air that activates the coating layer on paperboard surfaces. Parameters such as air velocity, nozzle geometry and the temperature distribution has a direct effect on the seal uniformity. Maintaining airflow and heat uniformity along the paper cup side seam surface is critical to ensure robust seals and prevent package failures (Tiitola, 2021). Alongside seam strength, sustainability criteria have driven the advancements of barrier coatings suitable with hot air sealing. Unlike traditional plastic laminates, newer coating applied to the paper cup side seam are engineered for biodegradability and recyclability while still being heat responsive. Advancements in biopolymer and nanocellulose coatings can now allow strong side seam sealing while meeting the needs for circular economy (Tyagi et al.,2021), this makes hot air nozzles even more relevant in the context of environmentally friendly designs. Shown in Figure 6 is the hot air nozzle used in the NEW TOP-138S paper cup manufacturing machine.

Figure 6. Hot air nozzle (LUT packaging laboratory).

For bottom sealing, nozzle design which can deliver heat effectively into folded areas is required. The effectiveness of hot air sealing in the bottom closure depends on the ability to evenly heat complex, overlapping paperboard layers without weakening the paperboard or scorching it. In multilayer packaging, modifying nozzle dimensions and positioning ensures that the adhesive or coating activates evenly (Morris, 2021), which is critical to withstand the vertical load of filled packages during storage and transport. Lastly, contemporary packaging equipment manufacturers are creating specialised nozzle configurations to improve sealing efficiency at the bottom of conical cups and containers. Cutting-edge machines incorporate nozzle systems with the capability of adjusting airflow angles dynamically, which enhances seal integrity across varying board thicknesses and cup geometries (Hörauf, 2024).

2.6 Defects in heating and forming

In paper cup manufacturing, the forming and heating are critical stages for creating leak-proof, robust seal, but a variety of defects can occur if these stages are not optimised. A frequent defect, improper sealing of the side and bottom typically occurs by insufficient heating or uneven heat distribution, which prevents the PE or PLA coating from softening

enough. As a result, bonding between the layers becomes weak, leading to leaks when the cup is filled. Seam integrity is extremely sensitive to temperature and airflow during heat sealing process (Ilhan et al., 2021). Shown in the following Figure 7 is the rim roll split.

Figure 7. Rim roll split near the seam (Bonifer et al., 2024).

Wrinkling and misalignments are another commonly observed defects which happen during bottom forming. If the hot air is not applied evenly, or the dwell time is short, the bonding between the multiple layers fails to bond uniformly. This creates small channels through which the contents of the cup leak out, this also compromises the mechanical strength at the bottom of the cup. Study on heat sealing show that mechanical stress and uneven heating in forming equipment worsen such wrinkling, directly lowering seal performance (Merabtene et al., 2022).

Overheating causes several defects, like scorching paperboard fibers and making coatings blister. During bottom sealing, the moisture that gets trapped between the layers of paperboard can turn into gas when it gets too hot. This makes bubbles or blisters that weaken the seam. Too much hot air can also burn the paper substrate or damage biodegradable coatings, which weakens both the strength and the barrier properties. Recent study shows that to avoid these problems, it is important to carefully control the design of the nozzle, the time it takes to seal, and the speed of the air. This is especially true now that more paper

cups are being made with compostable or bio-based coatings (Kukkonen, 2025). Shown in the following Figure 8 is the buckling of the side seam.

Figure 8. Side seam buckling near the bottom (Bonifer et al., 2024).

Overall, all these defects such as seal failure, wrinkling, scorching, and blistering happen when the delicate balance between the heat, airflow, and forming pressure are not optimised. Preventing these defects requires fine-tuning nozzle design, air temperature, and positioning of the bottom and side seam. As use recyclable and bio-based coatings are on the rise in paper cup manufacturing, defect prevention becomes even more important. Compared to conventional PE used in paper cups, these sustainable materials typically have narrower processing windows.

2.7 Computational fluid dynamics

One of the most widely tool used in modern thermal and process engineering is numerical simulation by CFD. Under varying boundary conditions, this tool provides a detailed means to predict fluid flow behaviour, heat transfer phenomena and turbulence characters. One of the most comprehensive platforms for modelling of complex thermal fluid interactions is Ansys Fluent, it captures jet impingement, conjugate heat transfer while coupling solid fluid domains (Uddin, 2024). In terms of nozzle design, CFD can particularly be valuable to

simulate flow of high-speed hot air through micro-jets interacting with side seam of coated paper surface. Dynamics that govern the heat-transfer process such as pressure, temperature, fluid velocity are captured in CFD simulation (Rachdi et al., 2025). Numerical models do not need physical prototypes to investigate the impact of parameter variation on system efficiency, such as impact of outer diameter, jet spacing, impingement angle or inlet pressure. Figure 9 shows velocity contour of a jet.

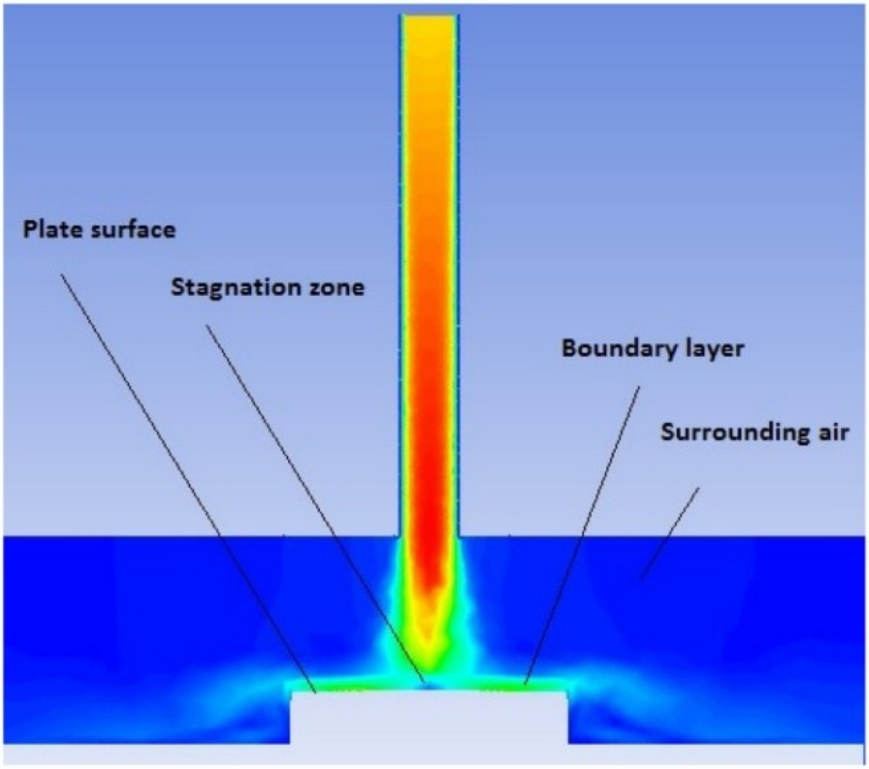

Figure 9. Velocity contour of a jet (P & V, 2022).

Modelling of highly transient and turbulent behaviour of the jets on paper surface is a critical challenge in such configurations. Wang et al. (2024) lists free-jet, stagnation and wall-jet as the three regions within impinging jet flow structure, each of these affect overall heat transfer efficiency in a unique manner. Resolving each zone requires spatial meshing and appropriate selection of turbulence model. Realizable k–ε and SST (Shear Stress Transport) k–ω models are included packages in Ansys Fluent which ensure accurate and stable capturing of local gradients.

In the context of paper cup side seam heating, CFD offers a reliable method to simulate the impingement of hot air over the paper cup side seam. By analysing the thermal and velocity contours, researchers can evaluate temperature uniformity, energy efficiency, and the degree of polymer activation. Moreover, CFD allows integration of conjugate heat transfer modelling, where heat conduction within the side seam paper is simultaneously solved with convective heat transfer in the air domain (Wright et al., 2022). The actual realistic heating process during the manufacturing process is represented by this approach.

Process optimisation through systematic modifications in geometry and operational parameters is supported by the application of CFD. Different nozzle designs with same boundary parameters can be compared effectively, identifying configuration that provides optimal heat distributions and reduced energy loss. In industrial packaging systems, this capability is critical, especially in high-speed paper cup forming. CFD serves as a virtual laboratory which allows designers to test effects of operating temperature, velocity, and nozzle geometry before implementation on production lines, this reducing trial and error testing. By providing detailed understanding of fluid dynamics and heat transfer mechanisms, CFD directly contributes to the optimisation of paper cup side seam heating, ensuring strong, uniform seals while promoting energy-efficient and sustainable manufacturing practices.

3 Methodology

This thesis focuses on the optimisation of the nozzles used in the side seam sealing setup for the paper cup manufacturing. The objective of the methodology is to comprehensively model, simulate, and analyse the thermal and fluid behaviour of various nozzle configurations. After simulating all the configurations, the most efficient configuration will be identified, which ensures uniform temperature distribution on the seam and also minimise energy loss. All modelling was done on Autodesk Fusion 360, and for simulation, Ansys Fluent was used. Shown in the following Figure 10 are the stages in CFD.

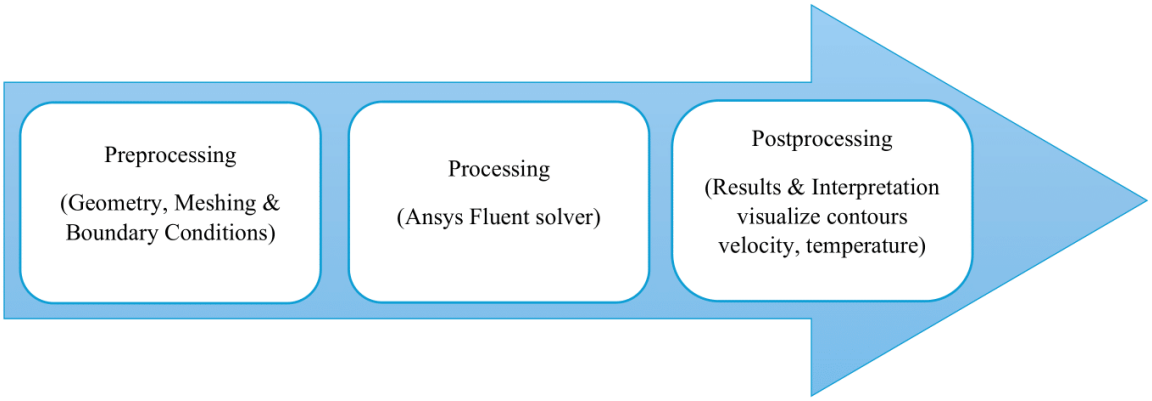

Figure 10. Computational fluid dynamics stages.

3.1 System description

The simulation recreates the side seam zone of the paper cup machine. In the process, hot air streams impinge on the paper seam to activate the PE coating, allowing bonding during the next mechanical sealing stage. The baseline nozzle is based on the NEW TOP-138S paper cup manufacturing machine used in LUT packaging laboratory.

The baseline nozzle consists of a single circular inlet that forces hot air through multiple micro-outlets, these outlets are arranged in a staggered pattern along its face. The air exits out of the multiple micro-outlets and impinges on the paper cup side seam. During this process, maintaining uniform heating along the seam is essential to guarantee consistent PE activation and reliable sealing.

The simulation consists of 3 principal domains, shown in Figure 11

1. The nozzle body (hot air flow region)
2. The paper representing the side seam
3. The ambient air enclosure, which allows the jets to expand and dissipate

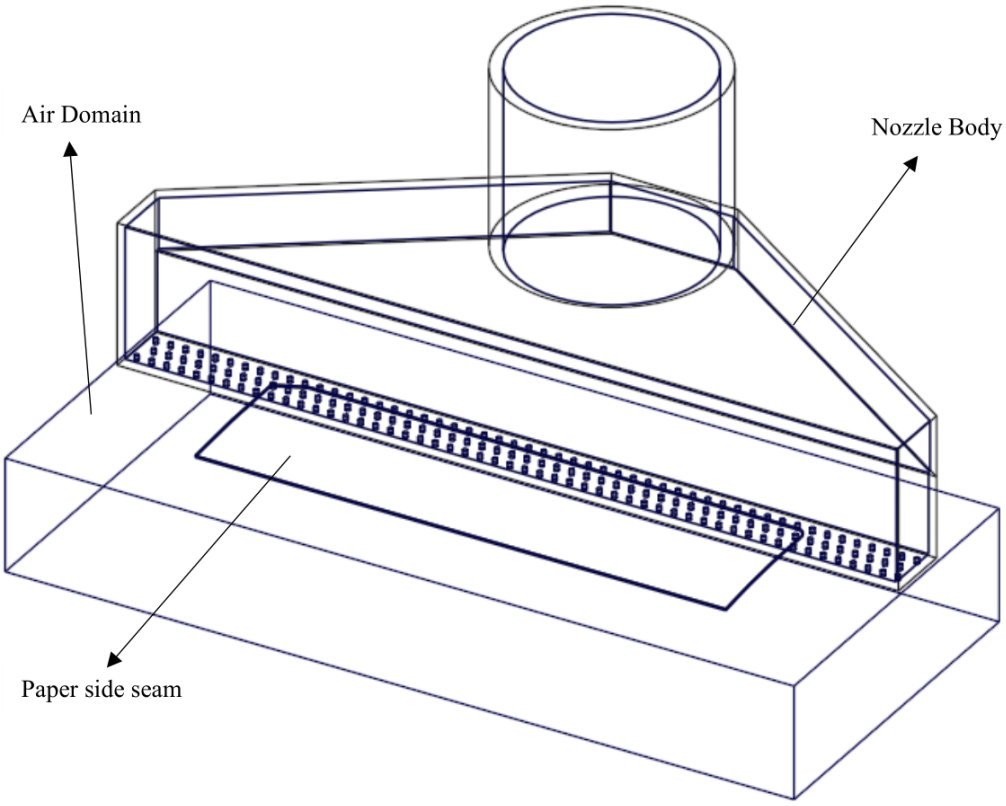

Figure 11. Principal domains of the CFD model.

3.1.1 Design basis and reference models

The modelling of baseline nozzle was done on the reference of nozzle used in NEW TOP-138S. The baseline nozzle contains one circular inlet through which hot air is blown and a flat outlet plate containing many uniformly distributed circular micro-outlets. Through these openings, heated air jets are blown towards the paper surface to activate the PE coating on the side seam prior to sealing.

The paper cup side seam was initially modelled by creating the whole paper cup blank based on the technical drawing shown in Figure 12, to ensure geometric accuracy. However, only the side seam region is exposed to the hot air jets during the sealing process, including the whole paper cup blank was unnecessary and computationally inefficient. Therefore, only the specific side seam portion corresponding to the actual heating zone was extracted and was used for simulation. This approach was to ensure accurate meshing and simulation of the thermal section while optimising computational resources and simulating efficiently.

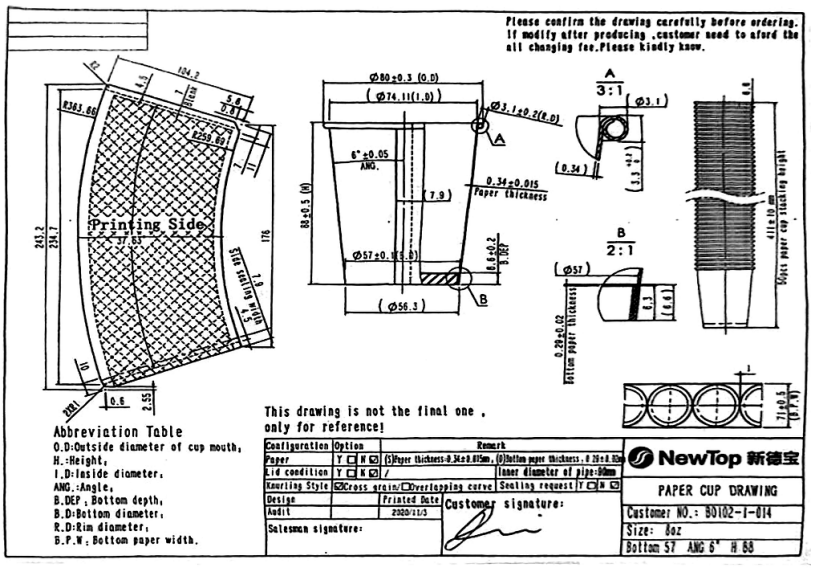

Figure 12. Technical drawing of paper cup.

The paper cup side seam was imported to Ansys SpaceClaim, then a thin PE layer was made created from the geometry to replicate the PE coating on the Cup stock. The thickness of the PE layer is 30 µm.

3.1.2 Optimisation of baseline nozzle

The optimisation of the baseline nozzle was done to enhance airflow uniformity and temperature distribution along the paper cup side seam region. 3 configurations were developed (Model B-D) through geometric modifications, every modification was done based on findings from previous jet-impingement heat transfer studies. Technical drawing of Model A can be found in Appendix 1.

Model B – Slotted outlet

In this configuration, the baseline configuration of circular outlets was replaced with slotted holes of 1 mm, the number of holes remained same as the baseline version. Slotted holes generate a continuous sheet of hot air. This modification aimed to minimise jet-to-jet interface and improve surface temperature uniformity. The design concept was based on previous study on slot jet impingement systems, which demonstrated improved heat transfer distribution and controlled surface temperatures in industrial heating applications (Zukowski, 2012). Shown in the following Figure 13 is the Model B nozzle. Technical drawing of Model B can be found in Appendix 2.

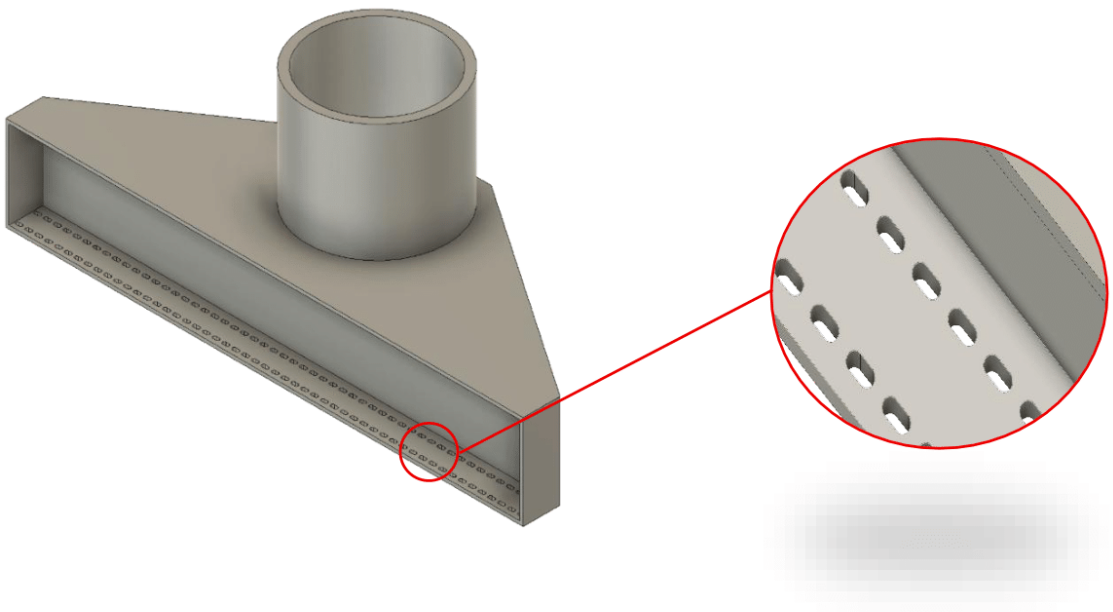

Figure 13. Model-B nozzle.

Model C – Smaller multi-row outlets

The second optimisation is modeled as 3 staggered rows with smaller diameter outlets, the configuration is designed to increase the number of impingement points and promote uniform heat distribution. By reducing individual jet size and arranging them in multiple rows, the convective interaction between adjacent jets enhanced temperature uniformity across the paper cup side seam. This optimisation approach aligns with the study that reports that decreasing jet diameter and optimising hole spacing remarkably increase thermal uniformity and overall heat transfer efficiency in multi-jet impigment systems (Culun et al., 2018). Shown in the following Figure 14 is the Model C nozzle. Technical drawings of Model C can be found in Appendix 3.

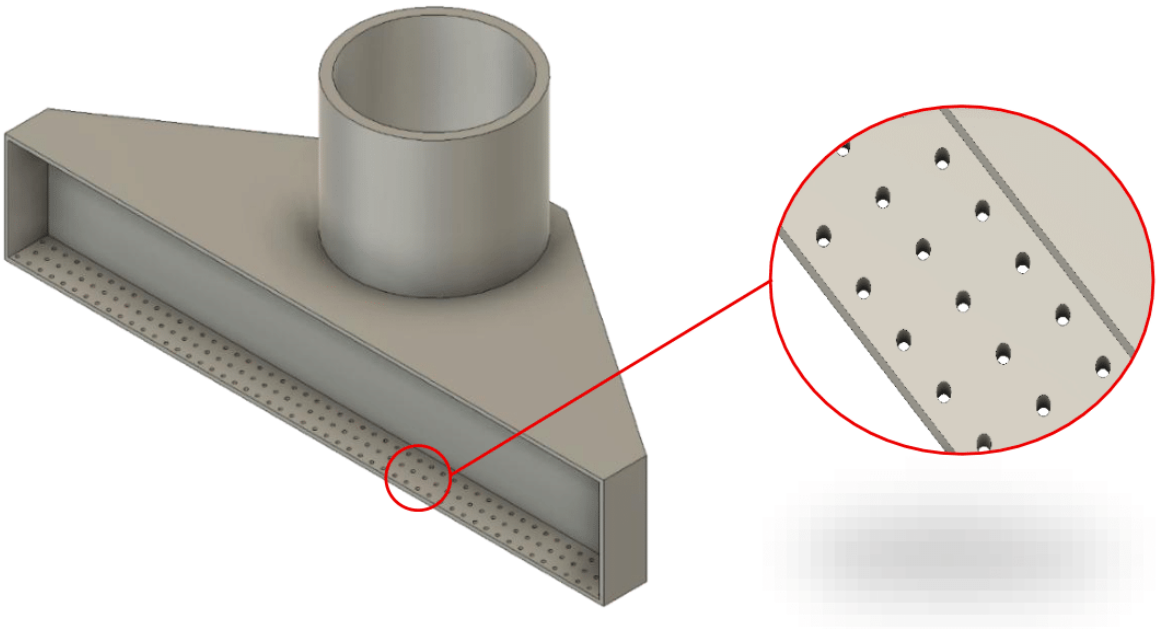

Figure 14. Model-C nozzle.

Model D - Enlarged outlets

The final configuration features larger outlet holes, Enlarging the size of the outlet relative to the baseline nozzle can reduce flow resistance and increase jet momentum, potentially impoving total heat flux but can decrease heat uniformity, Reports show that variations in hole pattern, spacing and Reynolds number directly affect impigment strength and heat

uniformity (Barbosa et al., 2023; Xu et al., 2024). These studies jointly indicate that enlarged holes enhance convective transfer whilst modifying the lateral spread of heat, this provides a valuable basis for comparative analysis in the present work. Shown in the following Figure 15 is the Model D nozzle. Technical drawing of Model D can be found in Appendix 4.

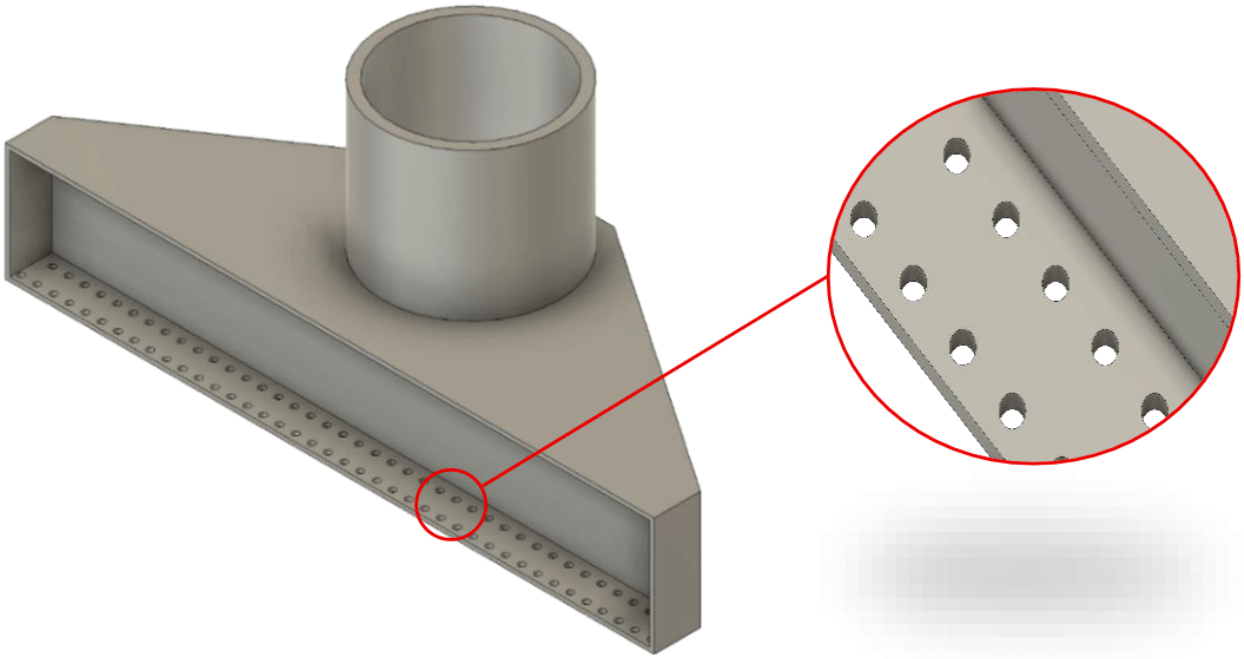

Figure 15. Model-D nozzle.

Each optimised design preserves the same inlet dimensions and external geometry as the baseline nozzle, this is to maintain consistent boundary and flow conditions. The four nozzle configurations (Model A-D) were subsequently used for CFD simulations to quantify the influence of outlet geometry on velocity distribution, surface temperature uniformity, and heat-transfer efficiency. Shown in the following Figure 16 and Table 1 are all the nozzle dimensions and the sizes of outlets, respectively.

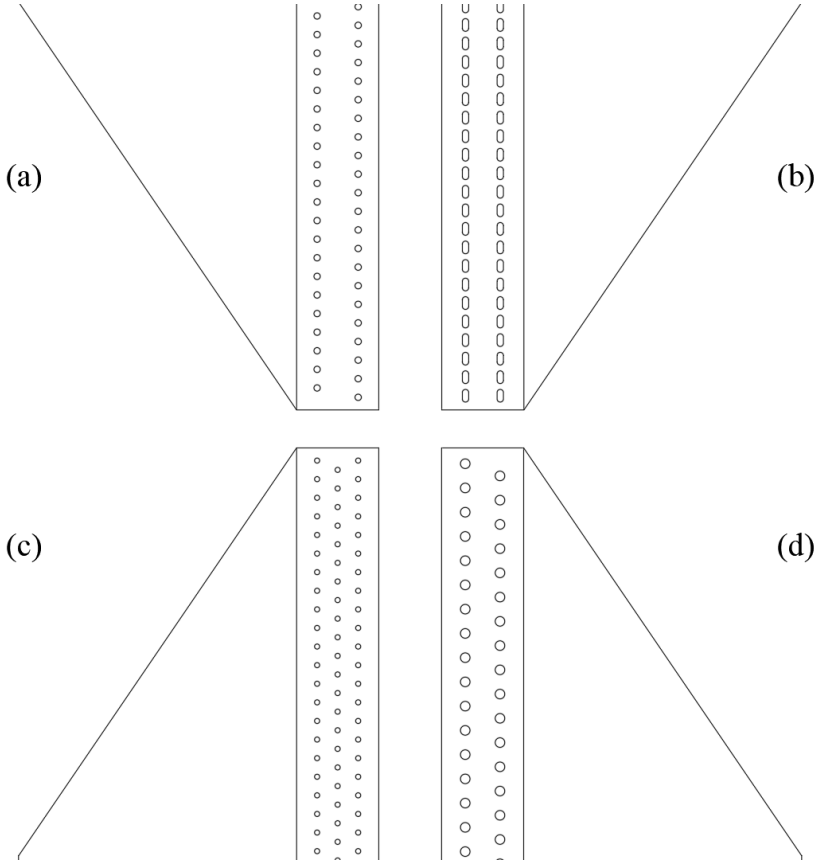

Figure 16. Nozzle models (a) Model A, (b) Model B, (c) Model C, (d) Model D.

Table 1. Model sizes.

Model	Type	Rows	Pitch [mm]	Diameter of outlets [mm]	No of outlets
Model-A	Baseline	2	2.94	1	104
Model- B	Slotted Outlets	2	1.93	1	104
Model-C	Smaller outlets	3	2.94	0.8	155
Model-D	Enlarged outlets	2	3.83	1.5	80

3.1.3 Preparation for simulation

The domain preparation in the simulation part is very crucial step in defining the regions for both fluid flow and heat transfer analysis. This process was carried out in Ansys SpaceClaim after importing the nozzle geometries that were developed in Autodesk Fusion 360.

Initially, the drawings were imported to SpaceClaim to make the assembly environment. Following which, a PE coating layer was created on the paper surface to replicate the thermoplastic layer. This coating was modelled as a separate solid body to allow distinct material property assigned during the Fluent CFD setup. After finalizing the PE layer, the position alignment between the paper and nozzle was adjusted to maintain a constant 2 mm air gap. This distance is in accordance with the clearance used in the NEW TOP-138S paper cup manufacturing machine and ensures realistic jet impingement conditions in the simulation. After alignment was confirmed, the internal flow volume of the nozzle was extracted, this operation removed the solid nozzle material and retained the hollow region through which hot air travels, from the inlet to the outlet holes, making this the fluid domain of the nozzle. Subsequently, an enclosure was created around the side seam paper specimen to make the surrounding ambient air region around the paper. The enclosure extended sufficiently beyond the impingement zone so that the complete flow field and potential jet depression effects can be captured. Finally, the enclosure around the paper cup side seam and the extracted flow volume of the nozzle were combined to form a continuous air domain, this represents the overall fluid region for CFD analysis. This combined domain allowed for the simulation of jet impingement on the paper surface and internal flow inside the nozzle.

Following the domain preparation, meshing was performed in Ansys Meshing to discretize the computational region into finite elements suitable for numerical analysis. A structured mesh was generated for the air domain to accommodate the complex geometry of the outlet holes and enclosure. Local mesh refinement was done, several surfaces sizing, body sizing was introduced to ensure optimal elements. The 2 mm gap between the outlet holes and the paper cup side seam surface, where the jet impingement occurs was refined to ensure sufficient grid density to resolve high-velocity and temperature gradients. Corser elements were applied farther from the impact region to maintain computational efficiency without sacrificing accuracy. This results in a mesh which provides balance between precision and computational cost, with element transition across the entire domain.

3.1.4 Boundary conditions and material assignment

After completion of the domain stage and meshing stage, suitable boundary conditions and material properties were defined to simulate realistic operating conditions of the hot air side

seam heating process. All boundary and physical inputs were defined in the Ansys Fluent setup module, these parameters were same for every model. The inlet boundary was assigned velocity inlet, which represents the entry of hot air through the singular nozzle inlet. The temperature and velocity at the inlet were same for all the optimised models ensuring consistency in all the simulations. The air enters the nozzle at the prescribed temperature and flow rate sufficient to achieve steady jet impingement on the side seam surface. The outlet boundary was specified as a pressure outlet at atmospheric pressure, allowing the hot air to come out of the outlet's computational domain freely. A backflow temperature was set to 25 °C to represent ambient conditions. The paper and PE surfaces were treated as a coupled wall, which allows conjugate heat transfer between solid and fluid domains. This setting allows heat to conduct through the paper and polymer layers while at the same time being transferred convectively from impinging air jets. The outer enclosure walls were set as stationary no-slip boundaries to confine the airflow while minimising artificial reflection of heat and momentum. These walls were considered to be adiabatic because heat losses to the surroundings were negligible compared to the convective transfer to the paper cup side seam. To capture density variations with temperature air was modelled to be an ideal gas, while the paper layer and the pe coating were defined as two different solids with distinct thermal properties. The following tables and figures show the boundary conditions in Table 2, the boundary location in Figure 17, and the material properties in Table 3.

Table 2. Boundary condition table.

Boundary	Type	Description
Inlet	Velocity inlet	Air velocity of 5 m/s, temperature 250°C
Outlet	Pressure outlet	Ambient pressure, backflow temperature 25 °C
Paper surface	Coupled wall	Conduction between air, paper, and PE coating
Enclosure walls	Stationary wall	No-slip, adiabatic boundary condition

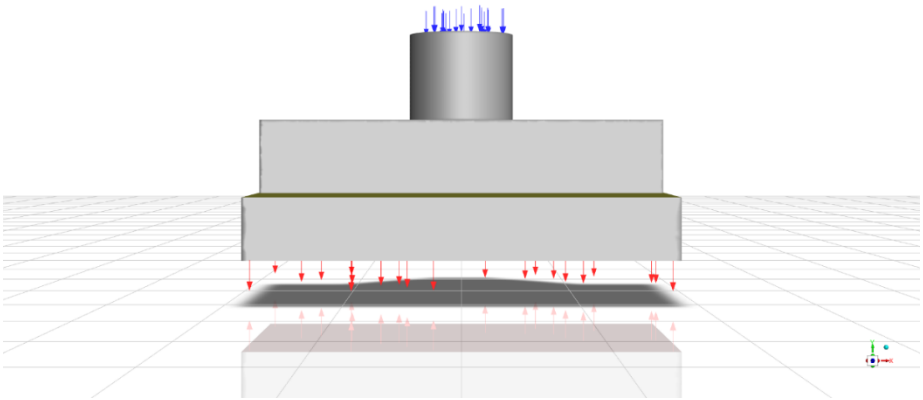

Figure 17. Boundary conditions in Ansys.

Table 3. Material properties.

Material	ρ [kg/m³]	κ [W/m·K]	c_p [J/kg·K]
Air	Temperature-dependent	0.026	1007
Paper	850	0.15	1400
PE	920	0.33	2300

3.1.5 Solver configuration and simulation setup

The numerical solution of the airflow and heat transfer was performed using Ansys Fluent, employing a steady-state, pressure-based solver suitable for thermal flows. The solver configuration was selected to accurately model the internal airflow and the hot air jet impingement heat transfer to the paper surface. The energy equation was activated to enable conjugate heat-transfer simulation between the air, paper and PE layer. The Realizable k–ε turbulence model with enhanced wall treatment was used, as it provides reliable predictions for jet-impingement flows and boundary-layer interactions in confined domains. For discretization, second-order upwind schemes were used for momentum, turbulence and energy equations to improve solution accuracy. Pressure velocity coupling was achieved by coupled algorithm, the convergence was monitored by tracking the residuals of all the governing equations.

3.2 Comparative evaluation approach

The comparison forms the analytical foundation for the thesis, which allows the performance of the various nozzle configurations to be assessed under identical boundary conditions and operating parameters. Four nozzle configurations were tested: the baseline design (Model A), and three optimised variants (Models B–D) featuring slotted, multi-row, and enlarged outlet geometries, respectively. All configurations were simulated using identical inlet temperature, velocity, and material conditions with Ansys Fluent, to ensure that any differences that are observed in performance are purely due to geometric variations.

The comparative procedure involved two key identical domains:

Thermal Comparison, to evaluate the heating performance of each nozzle, focusing on:

- Average Surface Temperature representing overall heat-transfer efficiency.
- Temperature Uniformity Index (UI), quantifying the evenness of heating across the paper surface.
- $T_{max} - T_{min}$ Range (ΔT), indicating the degree of temperature gradient on the PE-coated surface.

Velocity Comparison, to assess aerodynamic behaviour and its influence on heat distribution, using:

- Jet Velocity Intensity, describing the kinetic energy (KE) available for impingement.
- Flow Uniformity and Coherence, reflecting the stability and spatial consistency of the airflow pattern.

The temperature uniformity index was created using the following equation:

$$\mathrm{UI} = \left(1 - \frac{T_{max} - T_{min}}{T_{avg}}\right) \times 100 \quad (1)$$

Where, T_{max} is the maximum temperature, T_{min} is the minimum temperature and lastly, T_{avg} is the average temperature.

The calculated results for each model were then plotted in performance comparison plots, Average Surface Temperature vs Model and Uniformity Index vs Model. These plots visually represent the efficiency trends and enable direct ranking of the configurations. By analysing both thermal and velocity fields concurrently, this comparative approach provided understanding on how geometric modifications can influence the hot air behaviour and heat transfer performance. This systematic comparison not only verified the improvements achieved through the nozzle optimisations but also ensured that the analysis remained consistent.

4 Results and discussion

In this section the results of the CFD simulations conducted to analyse the performance of the four hot air-nozzle setups used in the sealing of the paper cup side seam. The objective of the analysis is to determine how optimisations made to the nozzle geometry influence air flow behaviour, heat transfer efficiency and temperature uniformity on the paper cup side seam.

The results are organized in three main sections. The first section is on the thermal performance of the nozzle, including average surface temperature, the maximum temperature, minimum temperature, and the temperature uniformity numericals derived from the simulations. The second section focuses on the velocity field characteristics, comparing jet intensities, coherence, and the impingement behaviour among the four models. The final section combines these findings into integrated discussion that correlates flow patterns with heat distribution performance, identifying the nozzle geometry that provides the best uniform and efficient heating profile.

4.1 Thermal comparison between nozzle configurations

The thermal analysis provides insight directly into how the nozzle geometry affects the heat transfer characters of the paper cup side seam. Since the sealing quality in the paper cup manufacturing depends mainly on achieving consistent and sufficient heating of the PE coating, temperature distribution across the side seam serves as the principal indicator of nozzle performance. Four nozzle models, baseline circular outlets (Model A), slotted outlets (Model B), smaller multi-row outlets (Model C), and enlarged outlets (Model D), all these models were simulated under identical temperature and flow conditions using Ansys Fluent. The results are analysed under average surface temperature, maximum temperature, minimum temperature and the temperature uniformity index. Together, these parameters reveal both the heating efficiency and homogeneity of the thermal exposure that the four nozzles can deliver.

4.1.1 Average surface temperature

The average surface temperature of the paper cup side seam provides an overall indication of the heating effectiveness of each nozzle configuration, this directly reflects the convective heat transfer performance in the system. In this analysis, the temperature of the air and the inlet velocity were kept identical for every configuration, to ensure that all variations are due to geometric and flow field differences.

The results show that there is a clear dependence of heating efficiency on outlet geometry. The Model C achieved the highest average surface temperature of 244.28 °C, followed by Model A at 239.04 °C. The Model D reaches a moderate average temperature of 228.11°C, while the Model B had the lowest average surface temperature.

The following trends shown in the Figure 18 show making modifications to the outlet shape and the jet density has an influence on the convective energy transferred to paper cup side seam. Model A, which has circular outlets in 2 rows, delivered concentrated jets that impinge strongly on localised regions on the paper cup side seam, which resulted in moderate overall heating. Even though coverage is limited, and significant temperature changes happen between the impinging jet cores and spaces between them. Model B produces a jet sheet due to the airflow diffusing across a larger area, these jet sheets stagnate and lose velocity rapidly within the 2 mm air gap. The consequence is that it produces a lower convective coefficient and the average temperature drops significantly, despite the apparent wider surface area exposure. This confirms that heating efficiency will diminish if jet velocity is not maintained, merely widening the outlet is not enough. By contrast, Model C consists of three rows of smaller jets of size 0.8 mm evenly distributed across the heating zone. The overlapping impingement zones sustain high convective flux and create balanced heat transfer across the paper surface. Despite the size of the outlets being smaller, the total number of jets compensates for individual jet losses, maintaining strong local momentum and high overall heat transfer rates. The result is a higher average surface temperature than all the other models, indicating the most efficient thermal performance.

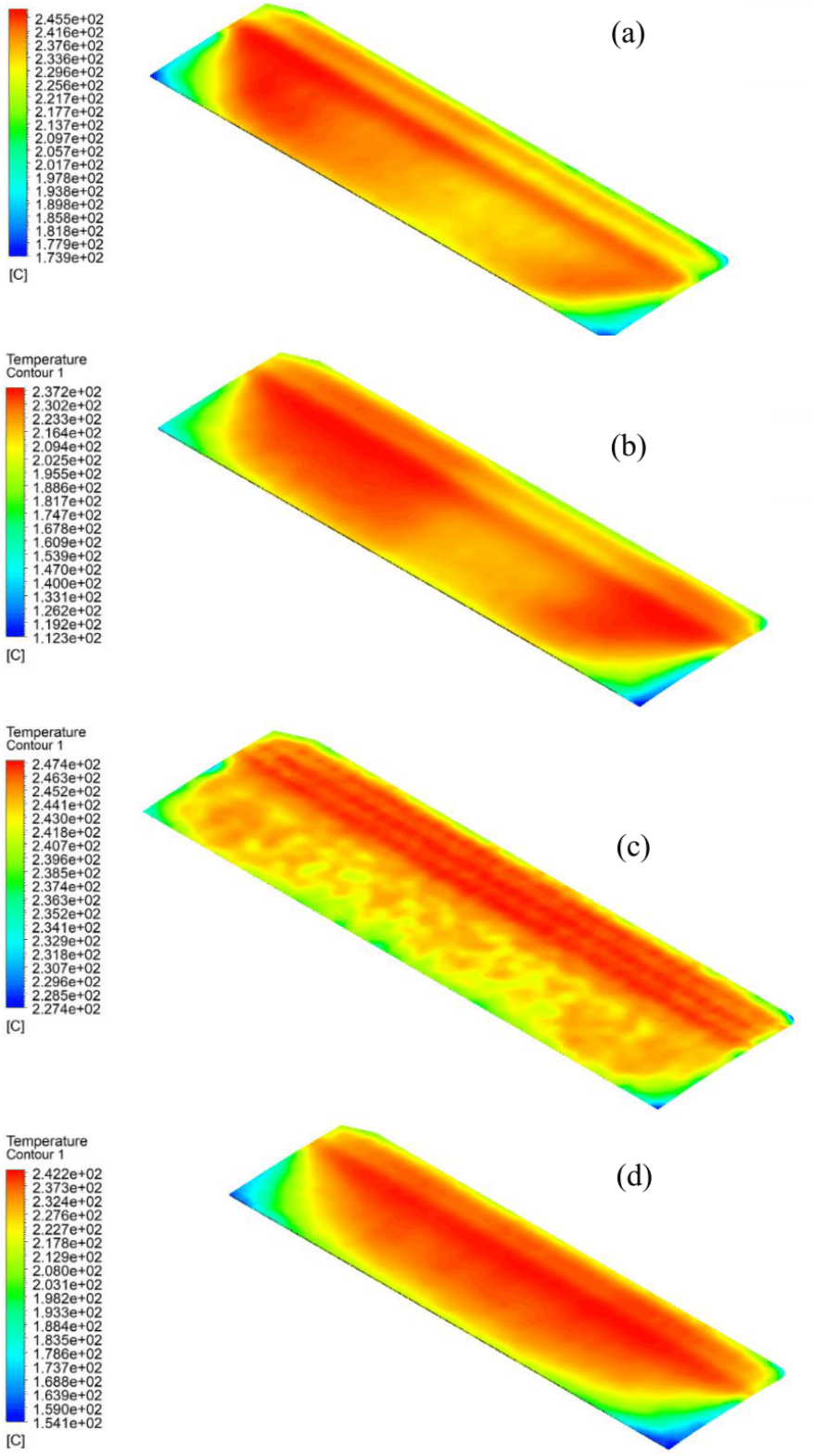

Figure 18. Heat distribution of (a) Model A, (b) Model B, (c) Model C, (d) Model D.

Model D reduced the pressure loss but also decreased momentum density, leading to a rapid jet expansion and premature merging. Although enlarging the outlets widens the effective footprint of heating, the reduced KE per unit area weakens the overall convective effect, causing to produce a lower T_{avg} than both Models A and C. Comparing the results quantitatively the difference between the best and the worst performing configurations (Model C and Model B) is over 25 °C, which is equivalent to a 12% increase in average temperature when using the optimised geometry. This shows that nozzle geometry modifications can significantly influence thermal efficiency under identical inlet conditions.

Moreover, it was found that temperature uniformity and average temperatures are correlated but not the same, for example, a nozzle may be able to produce high spikes in temperature but still performs poor in terms of heat transfer due to uneven thermal distribution. Model C was the most successful in combining high-intensity jets with uniform spatial coverage which resulted in both $Tavg$ and improved uniformity (discussed in Section 3.1.2). Figure 19 shows the $Tavg$ of the models and the deviation between T_{max} and T_{min} is shown through the error bars.

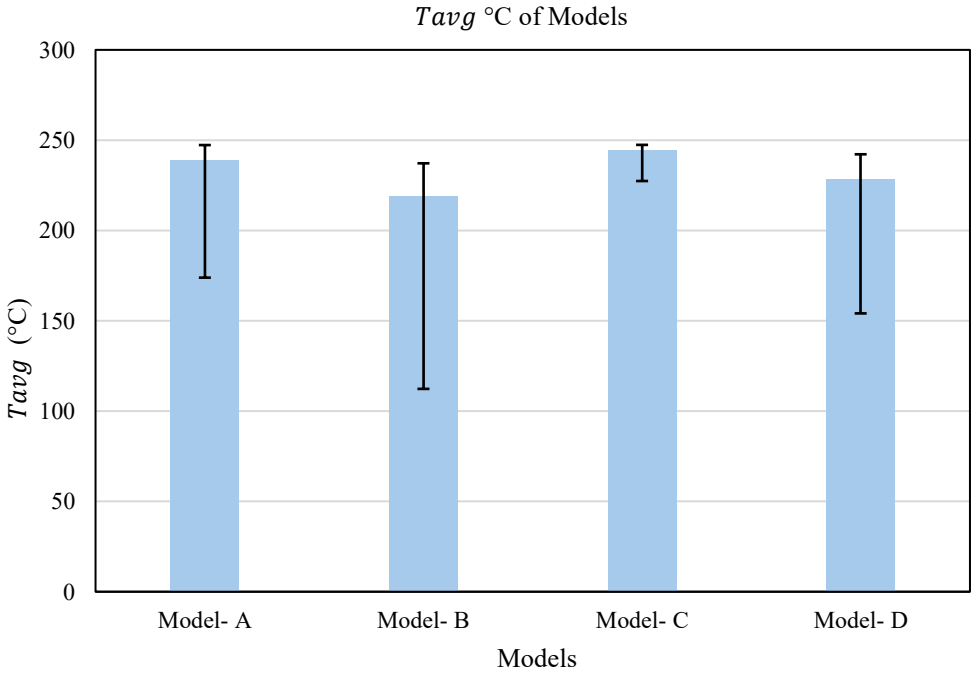

Figure 19. T_{avg} of Models A- D.

From a manufacturer's point of view, the elevated average temperature obtained from the Model C means that the PE coating on the paper cup side seam reaches its activation temperature more consistently, this will ensure that side seam will seal reliably during the sealing process. The more uniform and higher thermal field also allows the process to operate at slightly lesser inlet temperatures increasing the energy efficiency without compromising seal quality.

In summary, as shown Figure 19 the comparison of average temperatures establishes that Model C is thermally the most efficient configuration, delivering the highest mean temperature while maintaining balanced heating. Models A and D show moderate performance, and the Model B performs least effectively due to velocity loss and weak impingement intensity.

4.1.2 Temperature distribution and uniformity

While the average temperature provides an overall indication of the heat transfer efficiency, the distribution of that temperature across the paper surface is equally important. Uniform heating ensures that the PE coating softens consistently along the entire side of the paper, ensuring strong, defect-free seals form. Non-uniform heating, in contrast, leads to under-activated or overheated regions, which weakens the overall bonding strength and compromise the visual quality of the final cup. Therefore, evaluating UI is essential for identifying the most reliable nozzle configuration. The following Figure 20 is the UI of models.

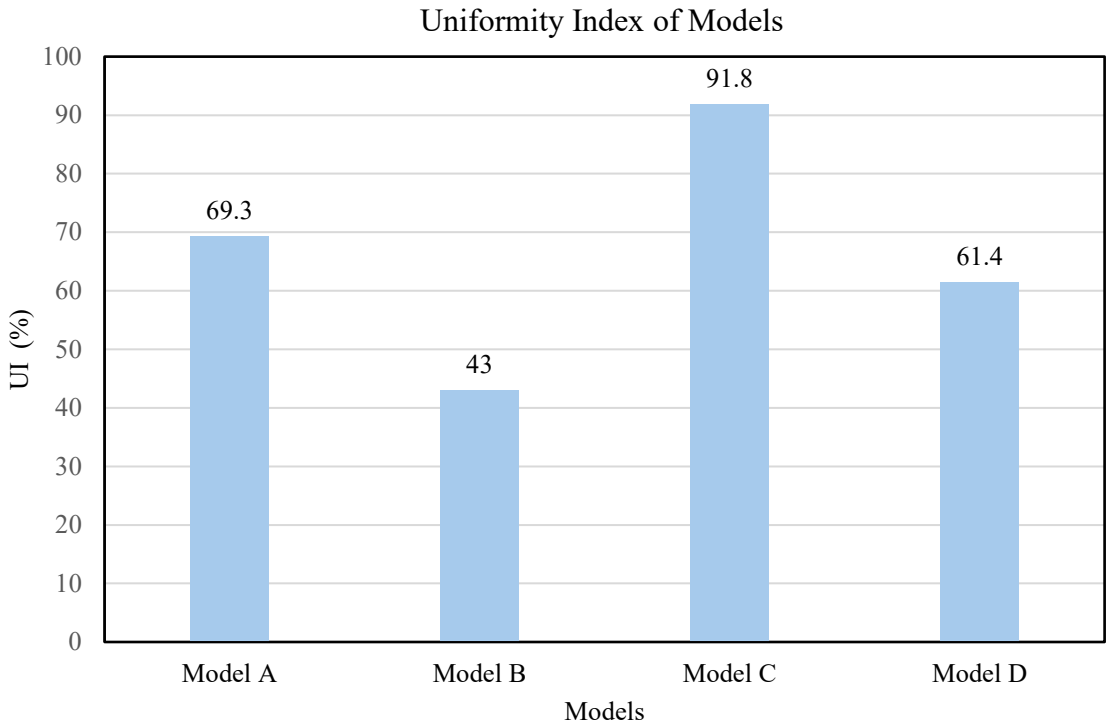

Figure 20. UI of models.

In Model A, hot streaks appear directly beneath the circular outlets, reaching the peak temperature of 247 °C, while the other regions were cooler at approximately 174 °C. The pattern reflects the localised pigment produced by the double row design. Although certain spots reached the activation temperature, however, the paper cup side seam does not heat uniformly, leading to irregular PE softening. The overall temperature range ΔT of 73 °C and UI of 69.3%, which indicates significant variation across the paper cup side seam surface. In Model B, the slot opening generates a broad but diffuse the heat field. The maximum temperature drops to 237 °C, while the minimum temperature plunges down to 112°C, producing the largest ΔT of 125 °C and the lowest UI of 43.0%. The overall heating intensity is insufficient, and the edges of the side seam remain cooler. The configuration demonstrates that an extended outlet without sufficient momentum fails to deliver effective or uniform heat distribution. In contrast, Model C shows a nearly homogenous temperature field with only minor variation across the paper cup side seam. Peak temperature is 247.4 °C, minimum temperature of 227.4 °C, and the resulting ΔT of 20 °C is the least among all the various models. The calculated UI of 91.8% confirms consistent heating. The multiple small jets interact and overlap each other, producing a stable layer of hot air that distributes heat evenly

across the paper cup side seam surface. The absence of sharp gradients show that the entire coating softens simultaneously, decreasing the risk of local over melting or incomplete bonding. Model C provides the most desirable temperature profile for the paper cup side seam. Model D shows intermediate performance, the maximum temperature was 242°C, the minimum temperature was recorded to be 154°C and the UI to be 61 %. The central region receives adequate heat, but the outer zone remains cooler, making it moderately non-uniform. It does not achieve the same level of uniformity as Model C.

The comparison in Figure 20, resulted in the order Model C > Model A > Model D > Model B, listed higher to lower in terms of uniformity index. Model C was 23% points better in UI as compared to Model A, this provides the confirmation of enhanced temperature consistency with geometric optimisation. Uniformity in Model B was very low as airflow was too widely spread which led to energy dilution, this signifies the importance of jet momentum. Although Model D exhibited noticeable edge cooling, which can cause weaking of adhesion in side seam during manufacturing stage, it overall performed better than Model B.

4.2 Velocity comparison between nozzle configurations

The flow field analysis provides critical information on how every nozzle geometry influences jet momentum, distribution and impingement characters. While the temperature field determines the heating outcome, the velocity field defies the mechanisms that drive convection and energy transfer. To ensure consistent comparison, all four nozzles were simulated under the same inlet velocity and temperature conditions.

4.2.1 Jet velocity intensity

The intensity of the hot air jets at the nozzle outlet determines the amount of KE available for the convection heat transfer. Differences in the outlet area and jet arrangements among all the four models significantly influence the magnitude and the distribution of jet velocity. Shown in the following Figure 21 are the velocity contours of Model A-D.

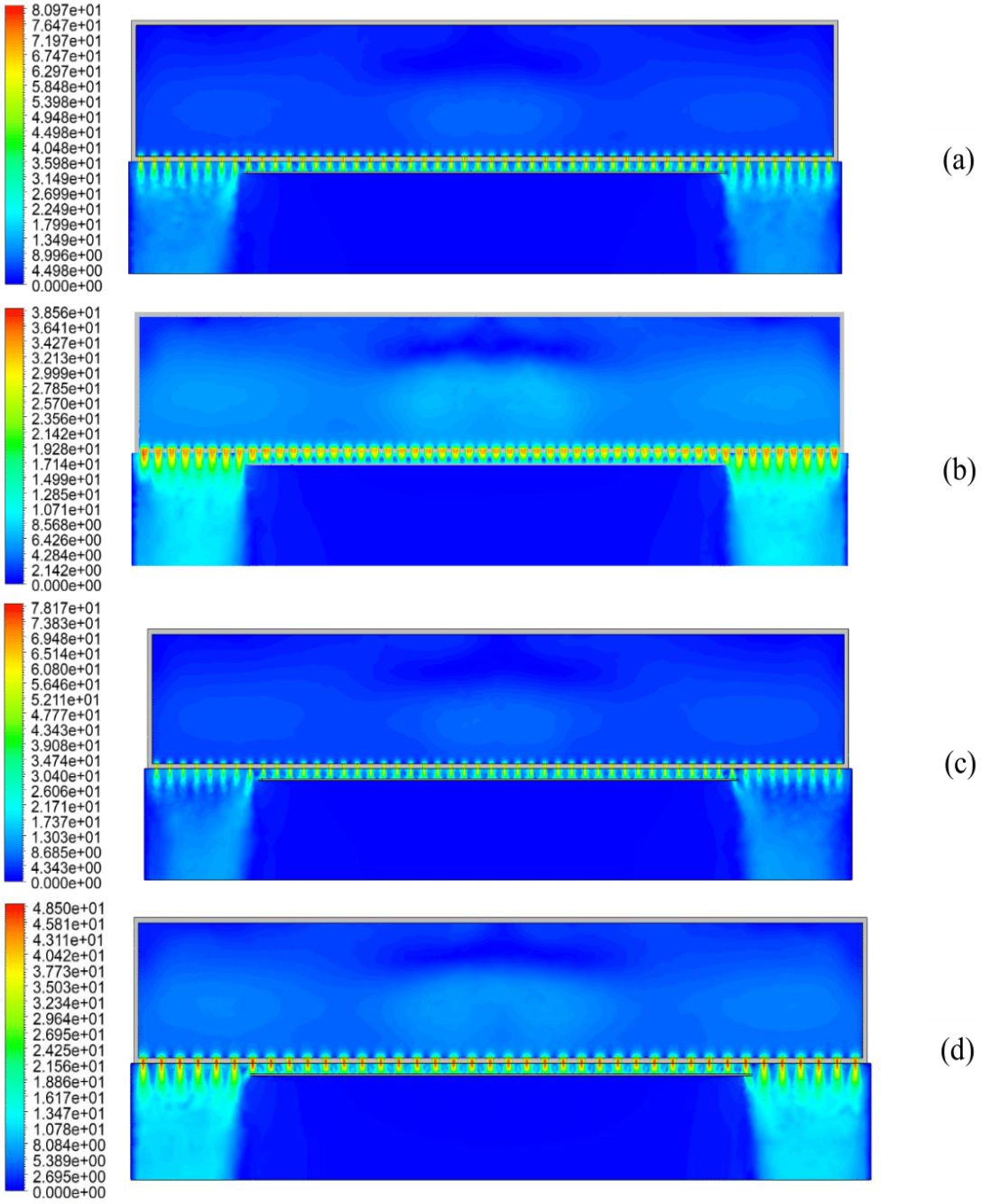

Figure 21. Velocity contours of (a) Model A, (b) Model B, (c) Model C, (d) Model D.

In the Model A, hot air exits the circular outlet with peak velocities of approximately 80 ms^{-1}, creating sharply defined stagnation zones on the paper surface. The concentrated jets enable strong localized convection but cause steep velocity gradients between the jets, leaving intermediate regions with relatively shallow air flow. In Model B, the slotted outlets increases the area per outlet, consequently decreasing the peak jet velocity to approximately

to 40 ms^{-1}, the air sheets expand laterally before reaching the paper. The flow lacks directional focus, which is required for efficient impingement, even though the flow covers a wider area. This leads to diminished convective potential. Model C improves the coverage and maintains high momentum. The staggered rows of 0.8 mm outlets create slightly overlapping jets that are coherent, they sustain near-uniform velocity distribution across the 2 mm gap between the nozzle and the paper cup side seam surface. The peak velocity remains high at 78 ms^{-1}, which is similar to the baseline model. Turbulence is enhanced and the momentum is preserved further downstream due to the cumulative interaction of neighbouring jets. Model D displays a different behaviour, even though the enlarged 1.5 mm outlets reduce pressure loss, the corresponding drop in outlet velocity is approximately 45 ms^{-1}, which results in a weaker jet core. These larger jets rapidly diverge and then merge before striking the paper cup side seam surface, creating a broad yet shallow velocity profile. As a result, it trades off jet impingement for wider flow spread.

Overall, the analysis confirms that the Model C archives the most balanced jet velocity intensity. It combines high local momentum with wide, stable coverage, providing the strongest foundation for uniform heat transfer across the paper surface. Models A and D show that adequate but uneven velocity distribution, while Model B exhibits the weakest impingement due to velocity decay and energy dispersion before contact with the side seam paper

4.2.2 Flow uniformity and jet coherence

Beyond the absolute velocity magnitude, the uniformity and coherence of the jet flow determine the overall stability of hot air delivery and its effectiveness in transferring heat evenly. Uniform jet behaviour ensures that the region of paper cup side seam surface receives comparable airflow energy, while coherent flow structures prevent early turbulence breakdown and uncontrolled diffusion.

The baseline model shows poor lateral connection, but the jets merge as isolated, high-speed streams that maintain strong individual cores. The velocity contours show narrow, well-defined regions of high momentum separated by wide zones of low-speed zones. While the overall uniformity across the paper cup side seam is moderate, the jet coherence of individual steam is excellent. Model B shows that the hot air exits the outlets like a continuous sheet

where separation between flow filaments is minimal, it sacrifices directional coherence and improves lateral connection. The merged sheets of air lose KE and begin to diffuse unevenly, within a short distance from the nozzle face, producing a low momentum zone near the paper cup side seam surface. This results in a smooth but weak velocity field with poor impingement intensity, this explains the reduced heating capacity and temperature non-uniformity observed in the previous section. Model C demonstrates superior aerodynamic performance; its staggered three-row pattern maintains coherence of individual jets limiting the overlap between adjacent flows. The interaction produces a consistent high-velocity layer across the impingement region, minimising the velocity fluctuations between jet cores and inter-jet spaces. Throughout the 2 mm gap the flow remains stable, with symmetrical expansions paper cup side seam surface. This model shows high flow uniformity, without significant loss in momentum, this is ideal for achieving uniform heat transfer. In Model D, the enlarged outlets lead to early jet expansion. The jets expand laterally and merge before maintaining coherent core structures, causing a non-uniform distribution across the paper cup side seam surface. Even though the coherence overall is wider than Model A, the central region shows stronger flow while the edges of the paper cup side seam surface receive lower velocity, producing moderate uniformity at best.

The comparative analysis of flow patterns across all for configurations confirms that Model C provides the most suitable and homogenous jet field. It archives a near uniform velocity profile over the heating surface, balancing localized jet coherence with large scale flow stability. In contrast, Model A is strong but discrete jets, Model B has diffused flow and Model D has rapidly expanding jets all exhibit limitations that hinder heat transfer. Shown here in Table 4 is the Qualitative comparison of jet coherence and turbulence behaviour.

Table 4. Qualitative comparison of jet coherence and turbulence behaviour.

Model	Jet coherence	Turbulence Behaviour
Model A	Strong (localized jets)	Independent jet cores
Model B	Weak (diffused sheets)	Early energy dissipation
Model C	Excellent (controlled overlap)	Symmetrical, stable turbulence
Model D	Moderate (rapidly merging jets)	Slightly asymmetric flow

These overall findings indicate that the flow uniformity is a primary contributor to heating uniformity. Only Model C archives the optimal combination of coherent yet distributed jets that preserve KE energy across the impingement area, forming the aerodynamic foundation for its superior consistency

4.3 Combined discussion: Flow–Thermal correlation and design insights

The temperature fields and airflow comparison revealed heating efficiency of each model is governed by nozzle behaviour, while temperature contours indicate thermal impact on paper cup side seam. Velocity ranges explained the mechanism of energy transferred. Simultaneous analysis of both results revealed that uniform jet momentum and coherent impingement are dominant factors when controlling uniformity in temperature.

A direct correlation exists between flow uniformity and thermal balance. Models A and C generate high velocity jets, but only Model C maintains even momentum across the outlet face. Its three-rowed pattern creates overlapping jets that sustain impingement, yielding the smallest temperature gradient ΔT of 20 °C and the highest UI of 91.8%. Model A's isolated jets overheat localized zones, while Models B and D lose KE before impact, producing cooler and uneven surfaces. Thus, improved jet overlap and coherence directly translate to more consistent heat transfer. The following Table 5 is the Aerodynamic and thermal performance indicators for all nozzle configurations.

Table 5. Aerodynamic and thermal performance indicators of models.

Model	Jet intensity	Flow uniformity	T_{avg} [°C]	UI
Model A	High	Moderate	239	69
Model B	Low	Poor	219	43
Model C	High	Good	244	91
Model D	Medium	Fair	228	61

The combined data confirm that Model C > Model D > Model A > Model B in overall performance. Model C achieves both high mean temperature and excellent uniformity due to its balanced jet arrangements. Model D performs reasonably well by widening flow coverage but cannot match Model C's coherence. Model A retains strong localized jets but lacks distribution, and Model B's broad yet weak sheet like airflow ranks the lowest. This hierarchy underscores that neither maximum velocity nor outlet area alone guarantees superior heat transfer, the optimal design balances jet intensity with spatial uniformity to sustain both energy density coverage.

5 Conclusions

This thesis was set out to analyse the baseline nozzle and provide an optimised nozzle if deemed necessary to increase heating performance of hot-air nozzles used in the side seam sealing stage of paper cup manufacturing. The side seam heating process, although a small part of the overall production line, plays a major role in determining whether a cup becomes structurally sound or ends up as waste. In many modern machines, especially high-speed models, even minor irregularities in heating can lead to failures such as leaking seams, weak bonding, or visible surface defects. Because of this, understanding the behaviour of airflow and temperature distribution around the side seam becomes essential. The study approached this challenge by combining CAD modelling in Autodesk Fusion 360 with CFD simulations in Ansys Fluent, allowing the heating behaviour of four different nozzle configurations to be examined under identical operating conditions.

The baseline model, which was used as the reference in the thesis, reflected a typical industrial design, it consists of two rows of circular outlets. Simulations of this design show, while it can deliver reasonably high temperatures, the heating pattern along the paper cup side seam surface remained uneven. Under each jet, distinct hot spots formed, while the regions between them remained cooler when compared. This non-uniformity helps explains why even small changes in coating or material conditions sometimes cause inconsistent sealing results in high-speed cup manufacturing lines. To address this, three modified nozzle setups were modelled and tested, a slotted outlet design, a three-row arrangement with smaller outlets, and a version with enlarged outlets. Each model as intended to spread heat differently across the paper cup side surface. The results demonstrate clear difference between each modified model. The slotted design, even though covering broader area, it lost jet momentum too quickly and produces the lowest average temperatures. The enlarged-outlet model performed better than the slotted model but still showed noticeable variations in temperature uniformity.

The most promising model is the multi-row configuration with smaller outlets (Model C), this design produced the most uniform heat distributions on the paper cup side seam. The smaller jets interacted in a way that smoothed out the temperature field, reducing the temperature differences across the paper cup side seam to a fraction of what was seen on

other models. This translates to more reliable activation of the coating and fewer potential defects when looking from a sealing point of view. Future work could include experimental validation or testing with different coating materials. Overall, this study shows that even making minor modifications to geometry can meaningfully improve both energy efficiency and sealing reliability in paper cup manufacturing.

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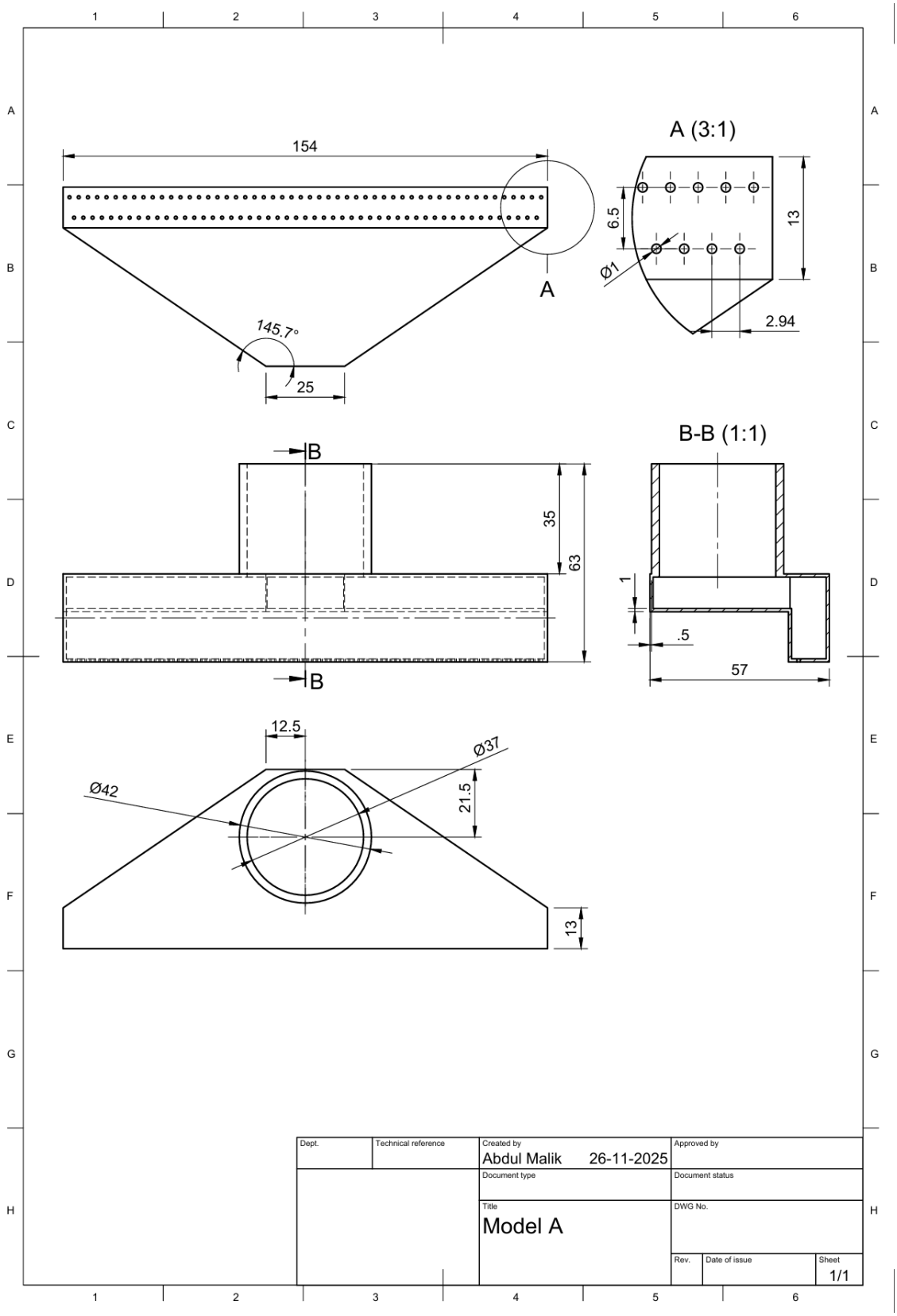
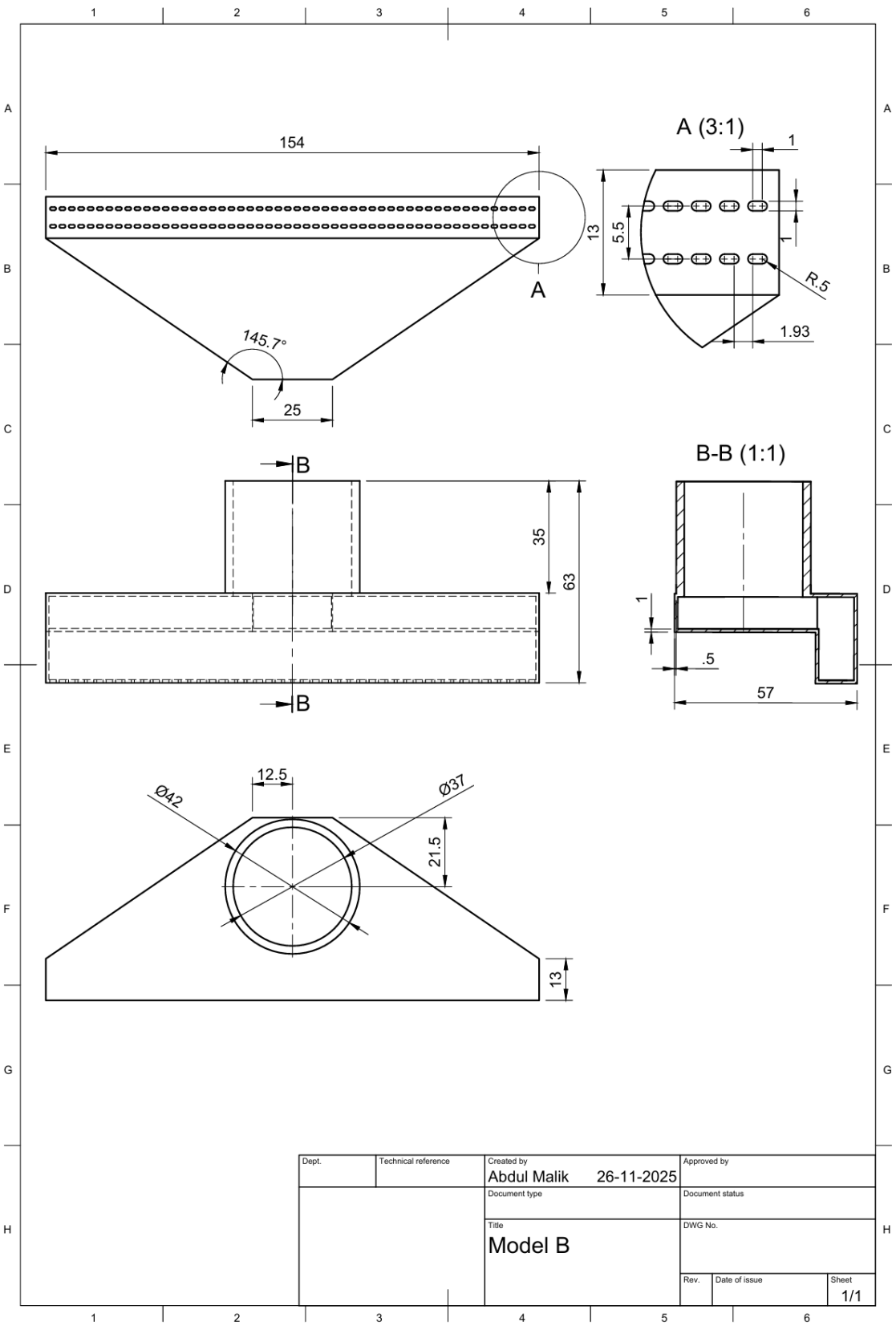
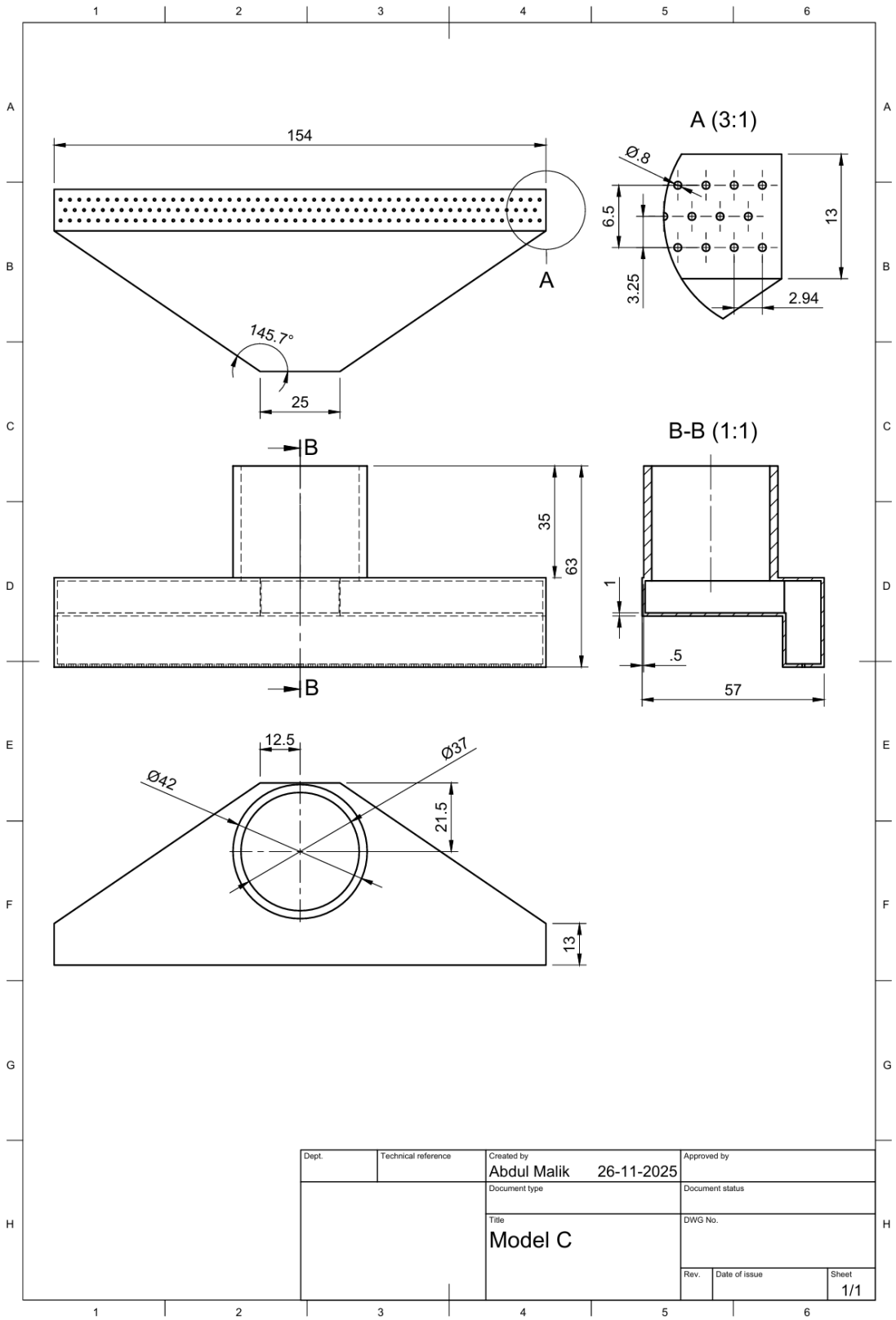
Appendix 1. Model A Technical drawing.



Appendix 2. Model B Technical drawing.



Appendix 3. Model C Technical drawing.



Appendix 4. Model D Technical drawing.