



AN INTEGRATED FFM-4 FRAMEWORK FOR FLUID FLOW MODELLING IN TEXTILE PROCESSING AND ADVANCED MANUFACTURING

Scientific paper
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ABSTRACT: Fluid flow modelling has become an essential engineering tool for improving manufacturing efficiency, product quality, and process sustainability across numerous industrial applications. In recent years, increasing attention has been devoted to the application of fluid mechanics principles and computational modelling techniques for optimizing manufacturing processes while reducing material consumption, energy use, and environmental impact. Among these applications, textile processing and advanced manufacturing technologies represent two important industrial sectors in which fluid flow plays a critical role in determining process performance and product characteristics. This paper presents a comprehensive review of fluid flow modelling in textile processing and advanced manufacturing technologies. The study discusses the fundamental principles of fluid mechanics and examines their application in textile dyeing, coating, finishing, printing, additive manufacturing, composite manufacturing, polymer processing, and industrial cooling systems. Current developments in Computational Fluid Dynamics (CFD), numerical modelling, and digital engineering tools are analysed with particular emphasis on process optimization, sustainability, and manufacturing efficiency. Based on the findings of the literature review, the authors propose the FFM-4 (Fluid Flow Modelling – Four Pillars) Framework, which integrates four complementary pillars for systematic fluid flow analysis in manufacturing systems: Fluid Properties, Flow Behaviour, Process Modelling, and Manufacturing Performance. The proposed conceptual framework provides a unified perspective for integrating fluid mechanics principles with modern manufacturing technologies while supporting sustainable production and interdisciplinary engineering applications. The proposed FFM-4 framework may serve as a conceptual foundation for future research focused on Computational Fluid Dynamics, Artificial Intelligence, Digital Twins, sustainability assessment, and intelligent manufacturing systems. Furthermore, it provides opportunities for strengthening the integration of fluid flow modelling across mechanical engineering, manufacturing technologies, and textile engineering.



Keywords: Fluid flow modelling; Computational Fluid Dynamics (CFD); Textile processing; Additive manufacturing; Sustainable manufacturing; FFM-4 framework.

INTEGRISANI FFM-4 OKVIR ZA MODELOVANJE STRUJANJA FLUIDA U TEKSTILNIM PROCESIMA I SAVREMENIM PROIZVODNIM TEHNOLOGIJAMA

APSTRAKT: Modelovanje strujanja fluida postalo je jedan od ključnih inženjerskih alata za unapređenje efikasnosti proizvodnih procesa, kvaliteta proizvoda i održivosti savremenih industrijskih sistema. Poslednjih godina sve veća pažnja posvećuje se primeni principa mehanike fluida i računarskog modelovanja u cilju optimizacije proizvodnih procesa, smanjenja potrošnje materijala i energije, kao i ublažavanja negativnih uticaja na životnu sredinu. Tekstilna industrija i savremene proizvodne tehnologije predstavljaju oblasti u kojima strujanje fluida ima značajnu ulogu u određivanju performansi procesa i kvaliteta finalnih proizvoda. U ovom radu dat je pregled primene modelovanja strujanja fluida u tekstilnim procesima i savremenim proizvodnim tehnologijama. Analizirani su osnovni principi mehanike fluida, kao i njihova primena u procesima bojenja, oplemenjivanja, premazivanja i štampe tekstila, aditivnoj proizvodnji, proizvodnji kompozitnih materijala, preradi polimera i industrijskim sistemima za hlađenje. Posebna pažnja posvećena je razvoju računarske dinamike fluida (Computational Fluid Dynamics – CFD), numeričkom modelovanju i digitalnim inženjerskim alatima sa ciljem unapređenja optimizacije procesa, održivosti i proizvodne efikasnosti. Na osnovu sprovedenog pregleda literature, autori predlažu FFM-4 (Fluid Flow Modelling – Four Pillars) konceptualni okvir, koji integriše četiri komplementarna stuba za sistematsku analizu strujanja fluida u proizvodnim sistemima: osobine fluida, karakteristike strujanja, modelovanje procesa i proizvodne performanse. Predloženi konceptualni okvir pruža jedinstvenu perspektivu za povezivanje principa mehanike fluida sa savremenim proizvodnim tehnologijama, uz podršku održivoj proizvodnji i interdisciplinarnoj primeni u oblasti mašinstva i tekstilne industrije. Predloženi FFM-4 okvir može predstavljati konceptualnu osnovu za buduća istraživanja usmerena na primenu računarske dinamike fluida, veštačke inteligencije, digitalnih blizanaca, procene održivosti i inteligentnih proizvodnih sistema. Pored toga, okvir doprinosi jačanju integracije modelovanja strujanja fluida u mašinstvu, proizvodnim tehnologijama i tekstilnom inženjerstvu.

Ključne reči: Modelovanje strujanja fluida; Računarska dinamika fluida (CFD); Tekstilni procesi; Aditivna proizvodnja; Održiva proizvodnja; FFM-4 okvir.

1. INTRODUCTION

The increasing complexity of modern manufacturing systems has significantly expanded the role of fluid flow analysis in industrial process optimization. Accurate modelling of fluid behaviour is essential for improving process efficiency, product quality, energy consumption, and resource utilization across numerous engineering applications [2,18].



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From polymer extrusion and additive manufacturing to textile dyeing, coating, and composite processing, fluid flow directly influences manufacturing performance, process stability, heat transfer, and final product characteristics [8,11].

The textile industry is undergoing rapid transformation driven by digitalization, sustainability requirements, and advanced manufacturing technologies. Traditional textile processes such as dyeing, finishing, coating, and fiber production involve complex fluid flow phenomena that determine chemical transport, heat transfer, mass transfer, and material distribution [9,10].

Simultaneously, modern manufacturing technologies increasingly rely on Computational Fluid Dynamics (CFD), numerical simulation, and process modelling to optimize manufacturing parameters while minimizing material waste and environmental impacts [16,17].

In advanced manufacturing, fluid flow modelling has become an indispensable engineering tool for analysing molten polymer behaviour during additive manufacturing, resin impregnation in composite processing, cooling system performance, lubrication mechanisms, and thermal management [8,11,12].

Although numerous studies investigate fluid flow within individual manufacturing processes, limited attention has been given to integrating textile processing and advanced manufacturing technologies within a unified perspective. Establishing such a connection is particularly important as sustainable manufacturing increasingly combines digital engineering tools with process optimization to improve resource efficiency, product quality, and environmental performance [4].

The aim of this paper is to review the role of fluid flow modelling in textile processing and advanced manufacturing technologies, highlighting common fluid mechanics principles, current industrial applications, and future research opportunities. Particular attention is given to sustainable manufacturing, computational modelling approaches, and the integration of fluid flow analysis across engineering and textile production systems.

2. FUNDAMENTALS OF FLUID FLOW IN MANUFACTURING SYSTEMS

Fluid flow represents one of the fundamental physical phenomena governing numerous manufacturing processes. The movement of liquids and gases directly influences heat transfer, mass transfer, pressure distribution, and material transport, thereby affecting process efficiency, product quality, and manufacturing reliability. Consequently, understanding fluid flow behaviour has become essential for designing and optimizing modern industrial production systems [2,18].

Fluid behaviour is commonly classified as either laminar or turbulent, depending on the Reynolds number, which represents the relationship between inertial and viscous forces within the flowing medium. Laminar flow is characterized by smooth and orderly fluid motion with minimal mixing between adjacent layers, whereas turbulent flow exhibits chaotic velocity fluctuations and enhanced momentum and heat transfer. In manufacturing applications, both flow regimes are encountered depending on process conditions, fluid properties, and equipment geometry [7,18].

Among the most influential parameters governing fluid flow are viscosity, density, pressure, flow velocity, and temperature. These properties determine flow resistance, pressure losses, and energy consumption while simultaneously influencing transport phenomena within manufacturing systems. In polymer processing and textile finishing operations, viscosity variations caused by temperature changes may significantly affect process stability, coating uniformity, resin impregnation, and material deposition quality [2,11].

The rapid development of computational modelling techniques has considerably improved the understanding of fluid flow behaviour in industrial applications. Computational Fluid Dynamics (CFD) enables numerical prediction of velocity fields, pressure distribution, turbulence intensity, heat transfer, and material transport before physical implementation of manufacturing processes. As a result, CFD has become an indispensable engineering tool for optimizing equipment design, reducing production costs, minimizing energy consumption, and improving process efficiency across numerous manufacturing technologies [16,18].

In both textile processing and advanced manufacturing technologies, fluid flow modelling provides valuable information for optimizing manufacturing parameters and improving product performance. Whether analysing dye penetration into textile structures, molten polymer extrusion during additive manufacturing, resin flow in composite processing, or cooling performance in industrial equipment, the underlying principles of fluid mechanics remain fundamentally identical. Therefore, fluid flow modelling represents a common engineering approach that connects various manufacturing technologies through shared physical principles.

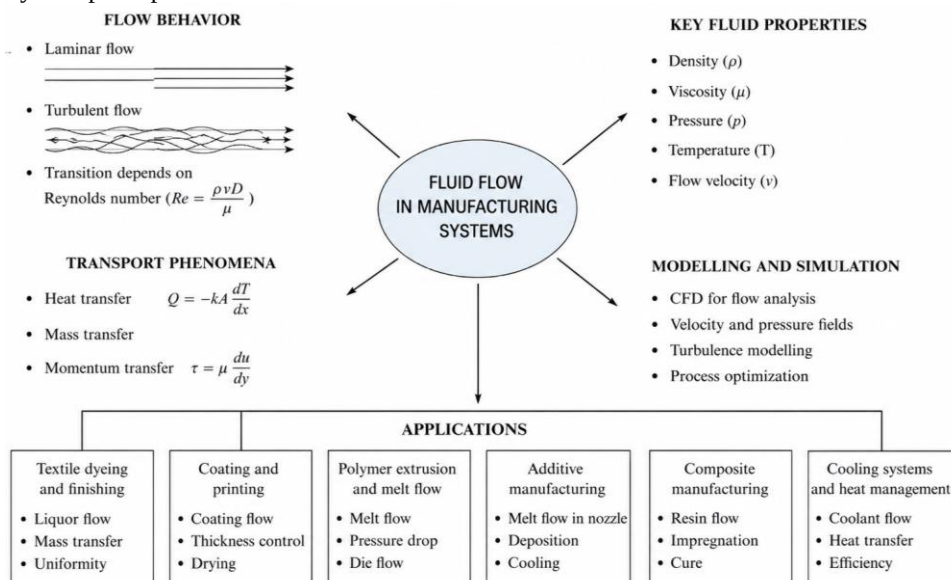


Figure 1: Fundamental fluid flow phenomena influencing manufacturing processes



3. FLUID FLOW APPLICATIONS IN TEXTILE PROCESSING

Fluid flow plays a fundamental role in numerous textile manufacturing processes, directly influencing product quality, process efficiency, resource consumption, and environmental performance. During textile production, liquids and gases are continuously involved in fiber formation, dyeing, finishing, coating, printing, washing, drying, and chemical treatment. The effectiveness of these processes largely depends on the controlled transport of fluids, heat, and dissolved chemical substances throughout textile structures [9,10].

One of the most important applications of fluid mechanics in the textile industry is dyeing, where the penetration and distribution of dye liquor determine color uniformity, dye fixation, and process efficiency. Proper control of flow velocity, pressure, temperature, and mixing conditions enhances mass transfer between the dye solution and textile fibers while reducing water, chemical, and energy consumption [9].

Fluid flow is equally important in textile finishing, where various chemical agents are applied to improve mechanical, thermal, or functional properties of fabrics. Processes such as padding, coating, impregnation, and washing require uniform fluid distribution to ensure consistent treatment over the entire textile surface. Poor flow control may result in uneven coating thickness, non-uniform chemical penetration, or defects that negatively affect product quality [10].

Modern textile printing technologies also rely on accurate fluid flow behaviour. The rheological properties of printing inks, nozzle design, droplet formation, and substrate interaction determine printing accuracy, color reproduction, and production efficiency. Numerical modelling and Computational Fluid Dynamics (CFD) are increasingly used to optimize ink transport, droplet deposition, and drying behaviour while minimizing material waste and process variability [17].

In recent years, sustainability considerations have significantly increased the importance of fluid flow optimization within textile manufacturing. Reducing water consumption, improving chemical utilization, minimizing wastewater generation, and enhancing energy efficiency have become primary objectives for modern textile production systems. Consequently, fluid flow modelling has evolved into an essential engineering tool for supporting environmentally responsible textile manufacturing and facilitating the transition toward more sustainable industrial processes [3,13].

Table 1: Fluid flow applications in textile manufacturing processes

Textile process	Role of fluid flow	Main objective
Dyeing	Dye transport and penetration	Uniform coloration
Finishing	Chemical distribution	Surface modification
Coating	Coating flow control	Uniform layer thickness
Textile printing	Ink flow and droplet formation	Printing accuracy
Washing	Water circulation	Contaminant removal
Drying	Air flow and heat transfer	Moisture removal



4. FLUID FLOW IN ADVANCED MANUFACTURING TECHNOLOGIES

Advanced manufacturing technologies increasingly rely on fluid flow modelling to improve production efficiency, process stability, product quality, and resource utilization. Although these technologies differ in terms of manufacturing principles, many of them involve similar fluid mechanics phenomena associated with molten materials, liquid resins, cooling media, lubrication systems, and heat transfer. Consequently, fluid flow analysis has become an essential engineering tool for process optimization across numerous industrial applications [16,18].

4.1 Additive Manufacturing

Among advanced manufacturing technologies, additive manufacturing represents one of the most significant applications of fluid flow modelling. During material extrusion processes such as Fused Deposition Modelling (FDM), molten polymer flows through the printer nozzle before being deposited layer by layer to form the final component. The rheological behaviour of the polymer, extrusion pressure, nozzle geometry, deposition velocity, and cooling rate strongly influence dimensional accuracy, interlayer bonding, mechanical performance, and surface quality of printed parts [8,12].

Numerical simulation and Computational Fluid Dynamics (CFD) have increasingly been applied to investigate melt flow behaviour inside extrusion nozzles, optimize printing parameters, and improve thermal management during layer deposition. These approaches contribute to higher process reliability, reduced material waste, and improved energy efficiency while supporting sustainable manufacturing strategies [6,8].

4.2 Composite Manufacturing

Fluid flow modelling is equally important in composite manufacturing processes, particularly during resin transfer moulding (RTM), vacuum-assisted resin infusion (VARI), pultrusion, and filament winding. In these processes, resin flow determines fibre impregnation quality, void formation, curing behaviour, and the final mechanical properties of composite structures. Accurate prediction of resin distribution enables improved process control while reducing manufacturing defects and material losses [11].

Advanced numerical models are widely used to predict resin filling time, pressure distribution, permeability effects, and temperature evolution during composite processing. Such simulations assist engineers in optimizing mould design and manufacturing parameters while improving production efficiency and structural performance [11,16].

In addition to resin filling analysis, fluid flow modelling plays a crucial role in predicting resin permeability through fibre reinforcements and evaluating the influence of processing parameters on composite quality. Parameters such as resin viscosity, injection pressure, fibre architecture, mould geometry, and temperature significantly affect resin infiltration and the formation of dry spots or voids within composite structures. Accurate numerical prediction of these phenomena enables engineers to optimize manufacturing conditions, reduce production defects, and improve the repeatability of composite manufacturing processes. Furthermore, coupling fluid flow simulations with curing kinetics and thermal

analysis provides a more comprehensive understanding of process behaviour, allowing improved control of dimensional accuracy, mechanical properties, and overall manufacturing efficiency. Consequently, integrated numerical modelling has become an important engineering approach for developing high-performance composite components used in aerospace, automotive, marine, and advanced engineering applications [1,11,16].

4.3 Cooling and Thermal Management Systems

Fluid flow also plays a crucial role in industrial cooling and thermal management systems. Efficient circulation of cooling fluids is essential for maintaining stable operating temperatures in manufacturing equipment, extrusion systems, injection moulding machines, and additive manufacturing devices. Proper heat removal improves dimensional stability, extends equipment lifetime, and reduces energy consumption during production [2].

The integration of CFD simulations into cooling system design enables engineers to analyse temperature distribution, coolant velocity, pressure losses, and heat transfer efficiency before physical implementation. As a result, computational modelling has become an indispensable tool for designing sustainable manufacturing systems with improved thermal performance and reduced operational costs [18].

Table 2: Comparison of fluid flow characteristics in advanced manufacturing technologies

Technology	Working fluid	Main fluid flow phenomenon	Engineering objective
Additive manufacturing	Molten polymer	Melt flow through nozzle	Printing accuracy
Composite manufacturing	Liquid resin	Resin impregnation	Void-free structures
Polymer extrusion	Polymer melt	Pressure-driven flow	Dimensional stability
Cooling systems	Coolant	Forced convection	Heat removal
Textile coating	Liquid coating	Surface flow distribution	Uniform coating
Resin Transfer Moulding (RTM)	Thermoset resin	Resin impregnation through fibre preform	Uniform impregnation and void reduction

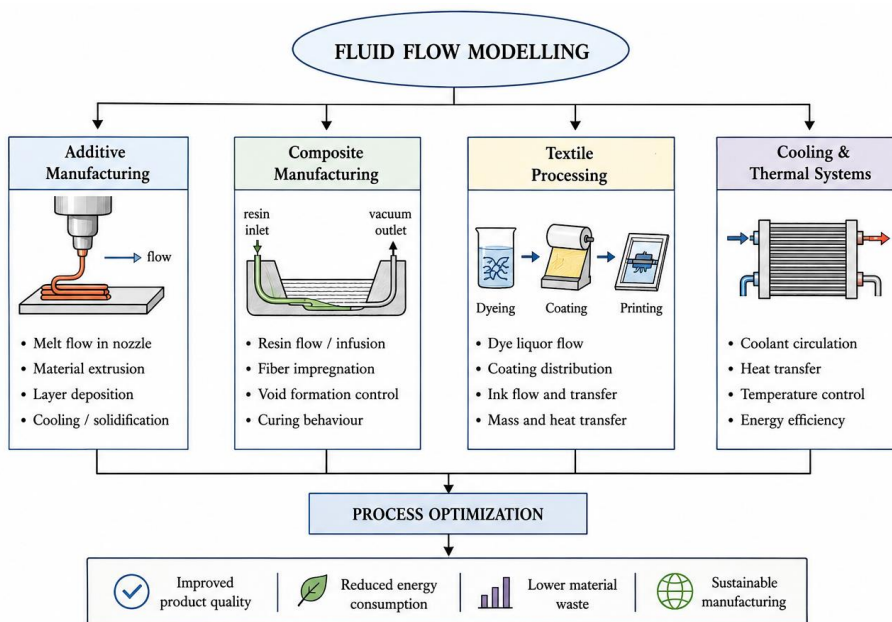


Figure 2: Integration of fluid flow modelling across advanced manufacturing technologies

5. PROPOSED FFM-4 FRAMEWORK FOR FLUID FLOW MODELLING IN MODERN MANUFACTURING

Based on the literature reviewed in the previous sections, it is evident that fluid flow modelling represents a common engineering approach connecting textile processing and advanced manufacturing technologies. Although fluid mechanics principles are applied in diverse industrial sectors, existing studies generally focus on individual manufacturing processes rather than providing an integrated perspective that combines textile production with advanced manufacturing systems. This observation highlights the need for a conceptual framework capable of systematically organizing the key elements influencing fluid flow analysis across modern manufacturing technologies [8,16,18].

To address this gap, the authors propose the **FFM-4 (Fluid Flow Modelling – Four Pillars) Framework**, which integrates four complementary pillars representing the essential components of fluid flow modelling in manufacturing systems. The proposed framework is intended to provide a systematic basis for understanding the interactions between fluid mechanics, computational modelling, manufacturing processes, and process performance while supporting future research in sustainable manufacturing.

The first pillar, **Fluid Properties**, includes the physical characteristics governing fluid behaviour, such as viscosity, density, pressure, temperature, and flow velocity. These

parameters directly influence transport phenomena, pressure losses, heat transfer, and material movement within manufacturing systems.

The second pillar, **Flow Behaviour**, describes the characteristics of fluid motion, including laminar and turbulent flow regimes, Reynolds number, momentum transfer, heat transfer, and mass transfer. Understanding these mechanisms is essential for predicting process stability and manufacturing efficiency.

The third pillar, **Process Modelling**, represents the integration of Computational Fluid Dynamics (CFD), numerical simulations, mathematical modelling, and digital engineering tools for analysing fluid behaviour before industrial implementation. These modelling approaches enable virtual process optimization while reducing development costs and experimental trials [17,18].

The fourth pillar, **Manufacturing Performance**, focuses on the practical outcomes of fluid flow optimization, including improved product quality, higher production efficiency, lower energy consumption, reduced material waste, enhanced sustainability, and optimized process control. These improvements contribute to more reliable and environmentally responsible manufacturing systems applicable to both engineering and textile industries [3,6].

The proposed FFM-4 framework demonstrates that fluid flow modelling should not be considered merely a computational analysis tool but rather an integrated engineering methodology capable of supporting process optimization across multiple manufacturing technologies. By connecting fluid mechanics principles with digital modelling and industrial applications, the framework establishes a unified perspective for future developments in sustainable manufacturing.

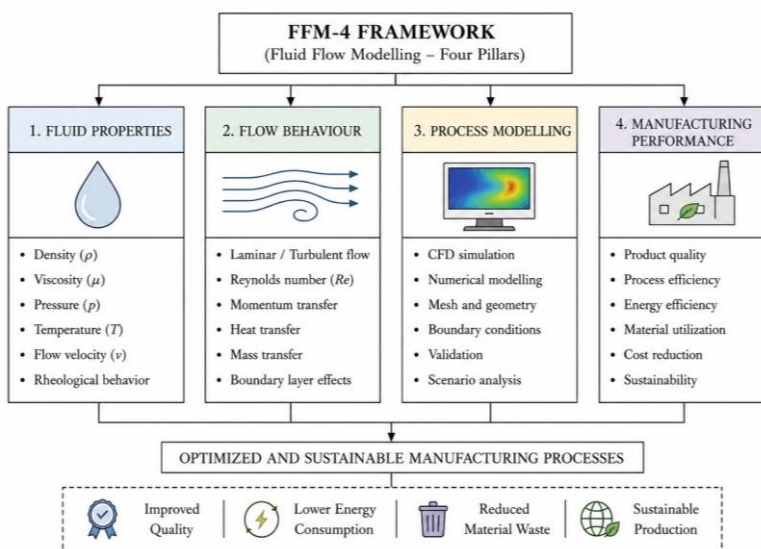


Figure 3: Proposed FFM-4 framework for integrating fluid flow modelling into modern manufacturing systems



6. FUTURE RESEARCH DIRECTIONS

The rapid evolution of manufacturing technologies is expected to further expand the role of fluid flow modelling in industrial process optimization. Future research should focus on developing more accurate numerical models capable of simultaneously describing fluid flow, heat transfer, material behaviour, and process interactions within increasingly complex manufacturing environments. Such integrated approaches will contribute to higher prediction accuracy while reducing experimental costs and accelerating industrial implementation [16].

One of the most promising research directions involves the integration of Computational Fluid Dynamics (CFD) with artificial intelligence (AI) and machine learning (ML) techniques. Data-driven models can significantly improve process prediction, parameter optimization, and real-time decision-making by combining numerical simulations with experimental and industrial data. These technologies are expected to play an increasingly important role in intelligent manufacturing systems and digital production environments [4].

The concept of Digital Twins also represents an important opportunity for future manufacturing systems. By combining real-time process monitoring with fluid flow simulations, Digital Twins enable continuous optimization of manufacturing operations, predictive maintenance, and adaptive process control. Such approaches may substantially improve manufacturing flexibility while supporting sustainable production and resource-efficient process management [15].

Another important research direction concerns the integration of fluid flow modelling with Life Cycle Assessment (LCA) and multi-criteria decision-making (MCDM) methods. Combining numerical simulations with sustainability assessment techniques may support the selection of environmentally friendly manufacturing strategies, optimized process parameters, and sustainable material alternatives. Decision-support methods such as the Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) could further assist engineers in evaluating manufacturing alternatives according to technical, economic, and environmental criteria [5,10,14].

Future investigations should also emphasize sustainable textile manufacturing, additive manufacturing, and composite processing by reducing water consumption, improving energy efficiency, minimizing material waste, and enhancing process reliability through advanced fluid flow modelling. These efforts are fully aligned with the principles of Industry 5.0 and the transition toward sustainable and digitally connected manufacturing systems [4,6].

7. CONCLUSION

Fluid flow modelling has become an essential engineering tool for understanding, analysing, and optimizing modern manufacturing processes. As demonstrated throughout this review, the principles of fluid mechanics are widely applied across both textile processing and advanced manufacturing technologies, including additive manufacturing,

composite manufacturing, polymer processing, and industrial cooling systems. Although these manufacturing technologies differ in their operational characteristics, they share common fluid flow phenomena that significantly influence process efficiency, product quality, energy consumption, and material utilization [8,18].

The literature review indicates that numerical modelling and Computational Fluid Dynamics (CFD) have considerably improved the capability to predict fluid behaviour, optimize manufacturing parameters, and reduce experimental efforts during process development. The increasing integration of digital engineering tools with manufacturing technologies further supports sustainable production by improving resource efficiency and reducing environmental impacts [6,16].

As the principal contribution of this study, the authors proposed the FFM-4 (Fluid Flow Modelling – Four Pillars) Framework, which integrates four complementary pillars: Fluid Properties, Flow Behaviour, Process Modelling, and Manufacturing Performance. Unlike existing studies that primarily focus on individual manufacturing technologies, the proposed framework provides a unified conceptual perspective for integrating fluid flow modelling across textile processing and advanced manufacturing systems.

The proposed framework may serve as a conceptual basis for future investigations involving Computational Fluid Dynamics, Artificial Intelligence, Digital Twins, and sustainability assessment methodologies. Furthermore, it may facilitate interdisciplinary collaboration between mechanical engineering, manufacturing technologies, and textile engineering while supporting the development of more efficient, sustainable, and digitally integrated production systems [4].

REFERENCES

- [1] Advani, S. G., & Hsiao, K. T. (2012). *Manufacturing Techniques for Polymer Matrix Composites (PMCs)*. Woodhead Publishing.
- [2] Çengel, Y. A., & Cimbala, J. M. (2018). *Fluid Mechanics: Fundamentals and Applications* (4th ed.). McGraw-Hill Education.
- [3] European Commission. (2020). *A new Circular Economy Action Plan: For a cleaner and more competitive Europe*.
- [4] European Commission. (2021). *Industry 5.0: Towards a sustainable, human-centric and resilient European industry*.
- [5] Finnveden, G., et al. (2009). *Recent developments in Life Cycle Assessment*. *Journal of Environmental Management*, 91(1), 1–21.
- [6] Ford, S., & Despeisse, M. (2016). *Additive manufacturing and sustainability: An exploratory study of the advantages and challenges*. *Journal of Cleaner Production*, 137, 1573–1587.
- [7] Fox, R. W., McDonald, A. T., Pritchard, P. J., & Leylegian, J. C. (2015). *Fox and McDonald's Introduction to Fluid Mechanics* (9th ed.). Wiley.
- [8] Gibson, I., Rosen, D. W., & Stucker, B. (2021). *Additive Manufacturing Technologies* (3rd ed.). Springer.



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„**Contemporary trends and innovations in the textile industry**“
17-18th September, 2026, Belgrade, Serbia

- [9] Gulrajani, M. L. (2010). *Colour Measurement: Principles, Advances and Industrial Applications*. Woodhead Publishing.
- [10] Holme, I. (2007). *Innovative Technologies for Textile Processing, Dyeing and Finishing*. Woodhead Publishing.
- [11] Mazumdar, S. K. (2002). *Composites Manufacturing: Materials, Product and Process Engineering*. CRC Press.
- [12] Ngo, T. D., Kashani, A., Imbalzano, G., Nguyen, K. T. Q., & Hui, D. (2018). *Additive manufacturing (3D printing): A review of materials, methods, applications and challenges*. *Composites Part B: Engineering*, 143, 172–196.
- [13] Niinimäki, K., Peters, G., Dahlbo, H., Perry, P., Rissanen, T., & Gwilt, A. (2020). *The environmental price of fast fashion*. *Nature Reviews Earth & Environment*, 1(4), 189–200.
- [14] Saaty, T. L. (1980). *The Analytic Hierarchy Process*. McGraw-Hill.
- [15] Tao, F., Zhang, M., Liu, Y., & Nee, A. Y. C. (2019). *Digital Twin driven smart manufacturing*. *Journal of Manufacturing Systems*, 48, 157–169.
- [16] Versteeg, H. K., & Malalasekera, W. (2007). *An Introduction to Computational Fluid Dynamics: The Finite Volume Method* (2nd ed.). Pearson.
- [17] Wijshoff, H. (2022). *Fundamental Fluid Dynamics Challenges in Inkjet Printing*. *Annual Review of Fluid Mechanics*, 54, 395–423.
- [18] White, F. M. (2016). *Fluid Mechanics* (8th ed.). McGraw-Hill Education.