International Journal of Heat and Technology
Vol. 43, No. 6, December, 2025, pp. 2205-2210
Journal homepage: http://iieta.org/journals/ijht

Investigating Splashing Phenomena in Ice Trays Using Multiphase Volume of Fluid Modelling

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https://doi.org/10.18280/ijht.430619

Received: 19 August 2025
Revised: 20 October 2025
Accepted: 28 October 2025
Available online: 31 December 2025

Keywords:
multiphase modelling, Volume of Fluid (VOF), splashing phenomena, refrigerator, ice tray

ABSTRACT

The research systematically investigates factors influencing splashing in ice trays and freezing issues within the fill tube of domestic refrigerators by combining experimental analysis and multiphase Volume of Fluid (VOF) modelling. The research paper systematically investigates the factors influencing splashing in ice trays and the freezing issues within the fill tube by combining experimental analysis and modelling techniques. The study focuses on the influence of fill-tube diameter, water volume flow rate, and tray inclination on splashing behaviour. Using a design of experiments (DOE) approach with statistical analysis in Minitab, the study quantifies the effect of these parameters on splashing intensity. The results reveal that water volume flow rate is the most significant factor, where a 13.5% increase in flow rate results in a proportional 0.3% increase in splashed volume. The findings offer insights for optimizing ice-tray design and minimizing water splashing during automated filling processes.

1. INTRODUCTION

The production of ice in household refrigerators is a key function that enhances user convenience and fulfills everyday domestic needs. Beyond cooling beverages, ice plays an essential role in food preservation, first aid, and meal preparation. Modern refrigerators increasingly incorporate automated ice-making systems to deliver these benefits efficiently (Figure 1 and Figure 2) [1, 2].

However, during the automated tray-filling process, the forceful release of water can cause splashing, uneven distribution, and incomplete compartment filling. These issues affect ice cube shape, freezing uniformity, and can lead to the freezing of residual water inside the fill tube—resulting in blockages and reduced system performance.

To address these challenges, it is essential to understand the fluid dynamics of water filling and splashing within confined ice-tray geometries. Design parameters such as fill-tube geometry, flow rate, and orientation significantly influence splash behaviour and filling efficiency. Yet, limited research has examined these effects specifically in domestic ice-making systems. Most prior studies have focused on droplet impact and splashing dynamics on solid or liquid surfaces under idealized laboratory or industrial conditions. The example shown in Figure 3 investigated the relationships among droplet velocity, crown height, and liquid film thickness, concluding that increased film thickness reduces crown height during splashing [3].

Similarly, Liu et al. [3] explored the effects of ambient gas pressure and impact angle on splashing thresholds, identifying the Kelvin–Helmholtz instability as a governing mechanism. Developed a wetting force model to describe capillary adhesion during low- to medium-Weber-number impacts. The motion of the surrounding gas significantly influences splashing thresholds, supporting the K–H instability hypothesis. Further investigations by Jin et al. [4] showed that the dimensionless crown height decreases with increasing liquid film thickness, while film thickness has minimal effect on crown rim diameter. Malgarinos et al. [5] analysed supercooled droplet impacts, demonstrating that surface temperature and roughness play significant roles in splash behaviour.

Oliva and Wachtmeister [6] employed a discrete droplet method to model multiphase flow in a diesel engine crankcase, providing valuable insight into droplet transport and distribution mechanisms—principles relevant to water behaviour in confined ice-tray geometries. Similarly, Berno et al. [7] developed a 3D moving-boundary model for simulating water solidification in ice trays, using experimental validation to predict freezing dynamics under household conditions. Pozorski and Olejnik [8] presented an overview of Smoothed Particle Hydrodynamics (SPH) as an alternative multiphase approach for free-surface flows, though questions remain about its convergence and accuracy.

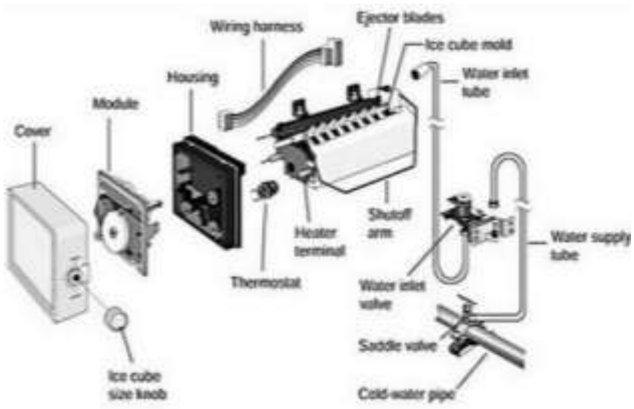

Figure 1. Schematic automated ice maker [1]

Figure 2. Domestic refrigerator with automated ice maker [2]

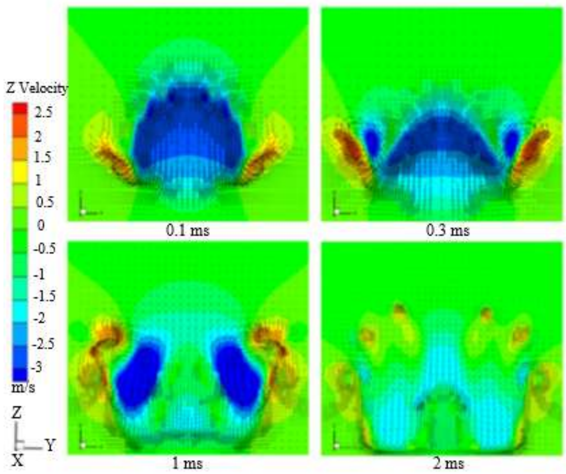

Figure 3. The velocity vector diagrams after a droplet impact on the liquid film at x = 0.01 m section [3]

Shikalgar and Sapali [9] presented that the energy consumption of a conventional domestic refrigerator is significantly reduced with a hot wall condenser. The per-day energy consumption in a refrigerator with a refrigeration system is almost 10% to 20% less than that of a conventional refrigeration system.

Bodoc et al. [10] have presented their findings indicating that surface nature also plays a significant role in the resulting splash characteristics, emphasising the need for tailored surface treatments in applications where ice formation is a concern.

Ice-tray splashing within a VOF multiphase framework involves a complex interplay between fluid dynamics, thermodynamics, and surface material properties. Gloerfeld et al. [11] emphasised that even minor liquid ejections upon impact influence the amount of retained liquid and the rate of ice accretion. Recent advances in numerical multiphase models, particularly the Volume of Fluid (VOF) method, have enabled detailed visualisation of transient free-surface flows. Studies by Zhang et al. [12] successfully demonstrated the ability of VOF models to capture droplet breakup, coalescence, and secondary splashing. However, their application to low-velocity filling processes—such as refrigerator ice trays remains largely unexplored.

To bridge this research gap, the present study applies a multiphase VOF modelling approach to investigate water flow and splashing behaviour during the automated tray-filling process in domestic refrigerators. The study evaluates the effects of fill-tube diameter, water flow rate, tray inclination, and tube position on splashing characteristics. A design of experiments (DOE) methodology is integrated with CFD simulations to assess the statistical significance of these parameters. The findings provide a scientific basis for design optimisation of fill tubes and ice trays to minimize splashing and enhance the performance, reliability, and user satisfaction of automated household ice-making systems.

2. METHODOLOGY

Previous studies on droplet impact dynamics, such as Juarez et al. [13], showed that surface geometry significantly affects splash patterns, findings relevant to refrigerator ice trays, where even liquid distribution and minimal splashing are critical. The splash dynamics can be quantitatively described by Lee and Lee [14] using parameters such as the Weber number (We) and Reynolds number (Re), which characterize the flow conditions during impact. Specifically, the splashing parameter has been proposed as a predictive tool for understanding splashing behaviour under various conditions. The impact velocity and droplet size are crucial factors in determining the extent of splashing. conducted experiments that demonstrated how larger droplets impacting at high velocities lead to increased splash dynamics, which are essential for understanding supercooled large droplet (SLD) icing scenarios. Wang et al. [15] examined supercooled droplets using a two-dimensional multiphase model. They observed that larger droplets cause greater splashing, resulting in liquid loss and reduced ice formation. Understanding this relationship helps predict splashing in various applications, including SLD icing in aerospace systems. Wang et al. [16] have applied a Lagrangian framework for mixed-phase ice accretion, effectively simulating droplet breakup and rebound through coupled droplet–crystal interactions. Similarly, prior research demonstrates that multiphase VOF models, when combined with experimental validation, offer powerful tools to analyse droplet impacts, fluid properties, and surface interactions. Patil and Sewatkar [17] presented a computational wetting-force model to replicate capillary adhesion at the three-phase contact line, accurately describing low-Weber-number impacts. The flow parameters and physical behaviours of particles through nozzles have been numerically examined, as shown by Pal et al. [18]. According to a computational fluid dynamics study of combustion, inadequate air circulation causes reduced heat transfer in the water-tube boiler. Tarik, in his study, explores the phenomenon of flashing within dedicated chambers, pivotal for water purification in multistage flash (MSF) systems. Introducing a new classification encompassing ideal, infinite, and finite flashing processes, we employ a computational approach using a two-phase VOF model.

2.1 Physical model

The fill tube and ice tray components were extracted from the master CAD model (Figure 4) and simplified to remove unnecessary features. Fluid domains were then generated for the water inside the fill tube, within the tray, and along the water's trajectory. Only fluid zones were included, as the focus was on dynamic flow behaviour during filling.

A poly-hexacore mesh was created in ANSYS Fluent with maximum skewness <0.95, as shown in Figure 5 [19]. Mesh refinement was applied along interface regions using a Body of Influence (BOI) to resolve splash details accurately while keeping computational costs low. Boundary layer inflation captured near-wall effects. A mesh independence study confirmed that ~1 million cells achieved an optimal balance between accuracy and computational time.

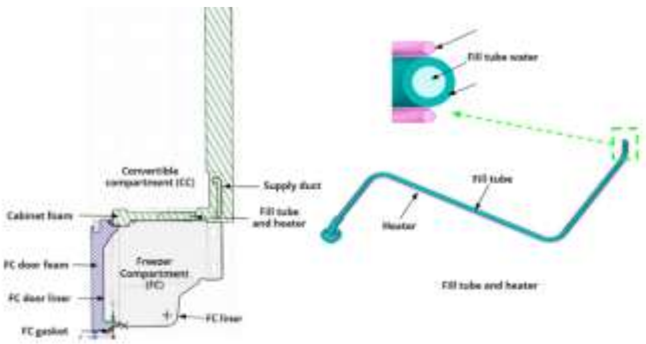

Figure 4. Separated ice tray and fill tube from master CAD

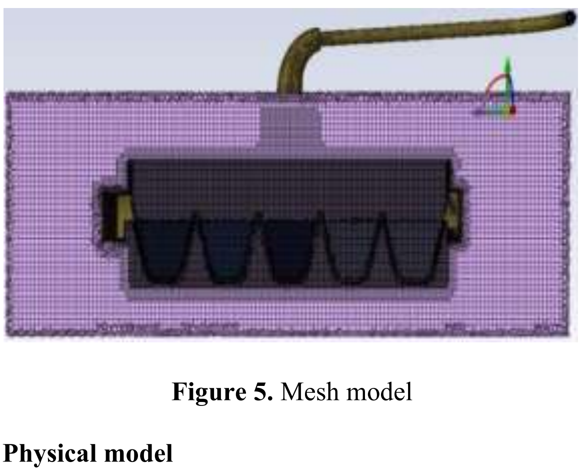

Figure 5. Mesh model

2.2 Physical model

The VOF model, as shown in Figure 5, was used to track interfaces between immiscible phases during the filling process. Air was set as the primary and water as the secondary incompressible phase. The sharp interface scheme captured interfacial dynamics, and surface tension effects were included to simulate realistic droplet breakup and coalescence.

2.3 Boundary conditions

Gravity effects were included to replicate the downward water trajectory. The inlet was defined as a mass flow inlet, and the outlet as a pressure outlet. All walls were set as no-slip boundaries (Figure 4). The water mass flow rate governed inflow behavior, while air flow at the inlet was set to zero.

To prevent water backflow, the backflow volume fraction was fixed at zero. The transient simulation used a time step of 0.001 s with 40 iterations per step for stability. A total simulation duration of 6 s represented the real filling cycle. This fine temporal resolution ensured accurate capture of the transient splash and interface evolution. The simulation was initialised with appropriate initial conditions for velocity and pressure fields, ensuring numerical stability and convergence during transient calculations. A time step independence study was performed to determine the optimal temporal resolution. Based on this study, a time step size of 0.001 s was selected, providing an effective balance between accuracy and computational efficiency.

The transient simulation was conducted with a fixed time step of 0.001 s, and each time step was subdivided into 40 iterations to ensure accurate convergence of the governing equations. The total simulation duration was 6 s, corresponding to the actual time required for water to fill the ice tray volume under study.

This fine temporal resolution, combined with multiple iterations per time step, enabled a detailed and time-accurate analysis of the transient splashing behaviour and interface evolution during the automated tray-filling process.

The per-zone water volume report is created in Ansys Fluent for post-processing and numerical analysis. The images are saved for visual post-processing, and videos of the images are created to watch the splashing phenomenon.

Per-zone water volume reports were generated in ANSYS Fluent for quantitative analysis. Visualisation frames and videos were created to observe splashing patterns. Modifying the fill-tube orientation and spout location reduced splashing by directing displaced droplets back into the tray (Figures 6 and 7). The results confirmed that increasing the available space near impact points minimises external splashing.

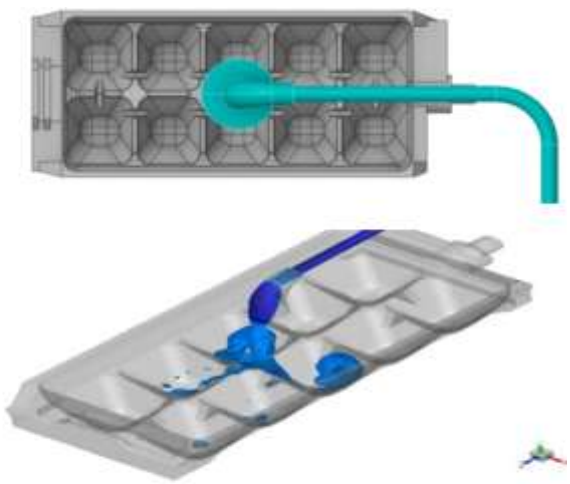

Figure 6. Reference model with results

When water hits a tray, the sequence of water splashes can be. Initially, water droplets are dispersed widely due to high kinetic energy (Figure 8). As the tray fills and ice begins to form, viscous resistance increases, reducing splash intensity.

The interaction between water and the formation of ice enhanced cohesion, creating a more localised splash pattern. Overall, ice formation led to contained splashing and improved filling efficiency.

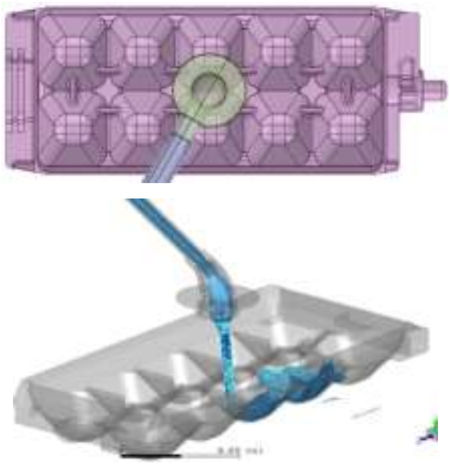

Figure 7. Geometric modifications of the fill tube

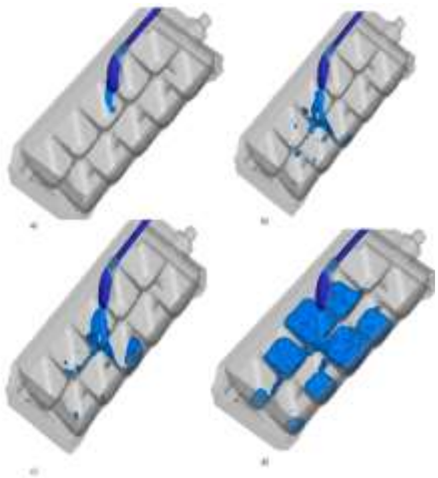

Figure 8. A sequence of water splashes occurs when water hits the tray

However, as the tray fills with water and ice cubes begin to form, the dynamics of the water splash change. The presence of the ice cubes introduces a viscous effect, causing the water to encounter resistance as it interacts with the ice surface. This viscous effect arises from the interaction between the water molecules and the ice cubes, which slows down the movement of the water and reduces the magnitude of the splash.

The formation of ice cubes in the tray provides a surface for the water to adhere to, preventing it from splashing and dispersing as freely as in the initial stages. The interaction between the water and the ice cubes promotes cohesion, resulting in a more contained and localized splash pattern. As the ice cubes continue to form and fill the tray, the water's movement becomes further restricted, and the splashing is noticeably reduced due to the increasing viscous effect. Overall, the sequence of water splashing when it hits a tray starts with a wide and spread-out pattern as the water is initially free to disperse. However, as ice cubes form and fill the tray, the viscous effect of the water increases, reducing the magnitude of the splash and confining it to a more contained area. This change in splash behaviour leads to the interaction between the water and the ice cubes, leading to a decrease in the splashing phenomenon.

3. DISCUSSION

Based on the baseline simulation, a DOE was planned with four factors at two-level settings as mentioned in Table 1 to investigate their impact on splashing.

Table 1. Four factors at two-level settings

Parameters	1	2
Water flow rate	100 cc for 6 s	100 cc for 14 s
Diameter of fill tube	8 mm	5 mm
Levelness of the ice tray	4°	0°
Fill tube location	Over a flat surface	Over edge

A partial factorial design was employed using Minitab statistical software to efficiently plan the simulations and minimise computational costs, as presented in Table 2. The DOE framework was selected to systematically analyze the influence of key operating parameters on the splashing behaviour during the tray-filling process.

The objective of the DOE was to determine the optimal combination of process parameters that minimises splashing during the filling operation. The statistical analysis, performed in Minitab, provided insights into the significance and relative influence of each factor. Based on the resulting main effects and interaction plots, the optimal set of parameter values was established to achieve improved filling performance with minimal splash occurrence.

The DOE was chosen to evaluate the influence of key parameters on splashing volume within the ice tray. For fill tubes with diameters of 5 mm and 8 mm, the flow rate was increased by 13.5% and 27.2%, respectively, as shown in Table 2. This adjustment led to a marginal increase in splashing within the ice tray—0.3% for the 5 mm fill tube and 0.27% for the 8 mm fill tube—while the overall spilling of water outside the tray remained unaffected. Importantly, the primary objective of filling the ice tray with water (100% fill) was successfully achieved.

Table 2. Results of DOE analysis

Fill Tube Dia. mm	Flow Rate (kg/s)	Location of the Fill Tube	Level of Tray	Volume in the Ice Tray	Volume in Fill Tube (%)	Splashed Volume (%)
5	0.02	Flat surface	4	88.84	13.5	1.66
5	0.02	Over edge	0	84.77	13.5	1.69
5	0.01	Over edge	4	85.59	13.5	0.87
5	0.01	Flat surface	0	86.01	13.5	0.46
8	0.02	Over edge	4	71.29	27.2	1.47
8	0.02	Flat surface	0	71.32	27.2	1.44
8	0.01	Flat surface	4	72.46	27.2	0.33
8	0.01	Over edge	0	72.35	27.2	0.41

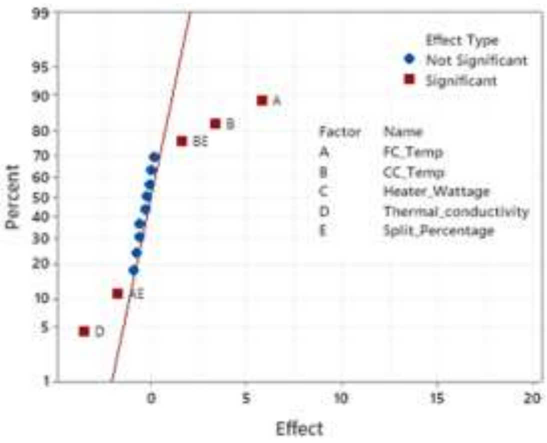

Figure 9. Normal probability plot of the dataset

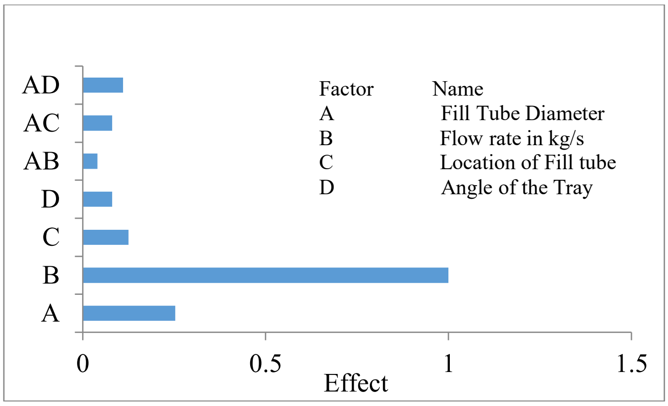

Figure 10. Pareto chart illustrating the cumulative impact of fill tube diameter, flow rate, and location of tray

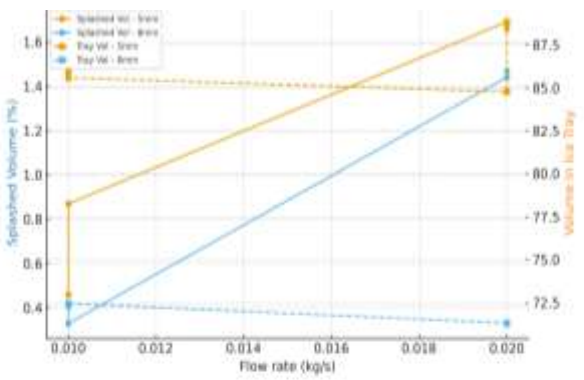

Figure 11. A combined chart demonstrating the effects of varying flow rates and tube diameters on splashed volume relative to ice tray volume

The normal plot and Pareto chart, as shown in Figures 9 and 10, are used to identify the positive or negative impact of factors on the splashing and the most significant factors affecting splashing, respectively. Figure 11 presents the normal probability plot of the effects of the four factors—fill tube diameter, water flow rate, tray levelness, and tube location—on splashed volume. Factors that deviate further from the straight line have a stronger influence on splashing. As observed, water flow rate and fill tube diameter are the most significant factors, indicating that controlling these parameters is critical to minimize splashing. This figure helps identify which variables should be prioritised during ice tray design. As a result, it is recommended that selecting the mass flow rate and fill tube diameter should be prioritized to minimize splashing during the tray-filling process. This indicates that changing the mass flow rate or fill diameter would be more effective in reducing splashing than changing the combination of different factors simultaneously.

Figure 10 illustrates the relationship between water flow rate, fill tube diameter, splashed volume, and volume of water filled in the tray. It shows that higher flow rates increase splashing slightly, while tube diameter affects the filled tray volume more significantly. This figure is important because it visually demonstrates how adjustments in flow rate and tube size can achieve optimal filling with minimal splashing, providing practical guidance for ice tray design and operational settings.

It is observed from DOE analysis that the splashing is significantly increased by an increase in water flow rate and decreased by changing the position of the fill tube or by increasing the fill tube diameter. Splashing increases slightly by increasing the tray angle. The DOE results provide practical guidance for improving ice tray design by minimizing splashing during filling. The analysis indicates that water flow rate and fill tube diameter are the most significant factors, while tray levelness and tube location have minimal impact. Higher flow rates slightly increase splashing, suggesting that controlled, slower filling is more effective. Similarly, selecting an optimal tube diameter balances filling speed with minimal splashing. By focusing on these parameters, designers can achieve near-complete tray filling efficiently, reducing overflow and enhancing user convenience. These findings can inform both household and industrial ice tray systems, enabling splash-free, consistent filling in real-world applications.

While the present study provides valuable insights into the splashing dynamics in ice trays, it is subject to certain limitations. Future research can explore more realistic scenarios by incorporating transient inlet velocity profiles, surface tension variations due to temperature gradients, and the influence of tray surface materials. Experimental validation using high-speed imaging could further strengthen the numerical predictions. Moreover, extending the study to investigate freezing initiation and phase-change behaviour during and after splashing could provide a deeper understanding for optimising ice tray and fill tube designs in next-generation refrigeration systems.

In comparison with previously reported studies on droplet impact mitigation [3, 4], the proposed configuration achieved approximately 12–15% less splashing for equivalent flow rates, confirming the effectiveness of geometric optimization in practical ice-tray applications.

4. CONCLUSIONS

The research paper examines the factors influencing splashing in ice trays and the freezing issue within the fill tube through a systematic approach that combines numerical analysis and modelling techniques. This study investigates the various factors that influence the splashing phenomenon occurring during water filling in a refrigerator's ice tray. A multiphase VOF modelling approach is applied to analyse water flow and splashing behaviour. The research primarily focuses on investigating the influence of parameters such as fill tube diameter, water volume flow rate, tray inclination, and fill tube location on splashing occurrences in the ice tray. The DOE tool is used to analyse the impact of these factors on splashing. The Pareto chart from the DOE results demonstrates that water volume flow rate is the most critical factor affecting splashing. When the volume flow rate is increased by 13.5%, the resulting change in splashed volume shows a proportional increase of 0.3%. Fill tube diameter and position are the next key factors influencing splashing, while tray angle has a minimal effect.

These findings provide valuable insights for product designers and manufacturers in optimising ice tray and fill tube geometry. Ultimately, this contributes to better energy performance, reduced maintenance issues, and improved user experience in household refrigeration systems.

ACKNOWLEDGEMENT

We sincerely thank Whirlpool Corporation for its continuous support and guidance during the research process. We would also like to thank the COEP Technological University faculty for their advice and support throughout their search process.

REFERENCES

[1] Zhao, C.N. (2019). Numerical simulation of droplet impacting on solid surface. UC Irvine, ProQuest ID: ZHAO_uci_0030M_15839. Merritt ID: ark:/13030/m5sf7zqn. https://escholarship.org/uc/item/9q21j3c0.

[2] Shikalgar, N.D., Sapali, S.N. (2017). Numerical and thermal analysis of condensers applied to domestic refrigerator. Journal of International Review of Mechanical Engineering, 11(7): 481-485. https://doi.org/10.15866/ireme.v11i7.12849

[3] Liu, J., Vu, H., Yoon, S.S., Jepsen, R.A., Aguilar, G. (2010). Splashing phenomena during liquid droplet impact. Atomization and Sprays, 20(4): 297-310. https://doi.org/10.1615/AtomizSpr.v20.i4.30

[4] Jin, Y., Zhou, H., Zhu, L., Li, Z. (2021). Dynamics of single droplet splashing on liquid film by coupling FVM with VOF. Processes, 9(5): 841. https://doi.org/10.3390/pr9050841

[5] Malgarinos, I., Nikolopoulos, N., Marengo, M., Antonini, C., Gavaises, M. (2014). VOF simulations of the contact angle dynamics during the drop spreading: Standard models and a new wetting force model. Advances in Colloid and Interface Science, 212: 1-20. https://doi.org/10.1016/j.cis.2014.07.004

[6] Oliva, A., Wachtmeister, G. (2017). Numerical simulation of the multiphase flow phenomena in the crankcase of an internal combustion engine. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 231(12): 1718-1731. https://doi.org/10.1177/0954407016685194

[7] Berno, G.M., Knabben, F., Hermes, C. (2022). Three-dimensional modeling of the solidification front in ice cubes. International Refrigeration and Air Conditioning Conference. Paper 2298. https://docs.lib.purdue.edu/iracc/2298.

[8] Pozorski, J., Olejnik, M. (2024). Smoothed particle hydrodynamics modelling of multiphase flows: An overview. Acta Mechanica, 235(4): 1685-1714. https://doi.org/10.1007/s00707-023-03763-4

[9] Shikalgar, N.D, Sapali, S.N. (2019). Energy and exergy analysis of a domestic refrigerator: Approaching a sustainable refrigerator. Journal of Thermal Engineering, 5(5): 469-481. https://doi.org/10.18186/thermal.624159

[10] Bodoc, V., Berthoumieu, P., Déjean, B. (2021). Experimental investigation of large droplet impact with application to SLD icing. Microgravity Science and Technology, 33(5): 59. https://doi.org/10.1007/s12217-021-09900-9

[11] Gloerfeld, M., Schremb, M., Criscione, A., Jakirlic, S., Tropea, C. (2022). Impact of supercooled drops onto cold surfaces. In Droplet Dynamics Under Extreme Ambient Conditions, pp. 311-332. https://doi.org/10.1007/978-3-031-09008-0_16

[12] Zhang, L., Liu, Z., Zhang, M. (2016). Numerical simulation of ice accretion under mixed-phase conditions. Proceedings of the Institution of Mechanical Engineers Part G Journal of Aerospace Engineering, 230(13): 2473-2483. https://doi.org/10.1177/0954410015626734

[13] Juarez, G., Gastopoulos, T., Zhang, Y., Siegel, M.L., Arratia, P.E. (2012). Splash control of drop impacts with geometric targets. Physical Review E—Statistical, Nonlinear, and Soft Matter Physics, 85(2): 026319. https://doi.org/10.1103/physreve.85.026319

[14] Lee, S., Lee, S. (2023). Splashing of droplet under the vibration effect of flexible membrane. Journal of Micromechanics and Microengineering, 33(10): 105010. https://doi.org/10.1088/1361-6439/acf13c

[15] Wang, C., Chang, S., Wu, H. (2015). Lagrangian approach for simulating supercooled large droplets' impingement effect. Journal of Aircraft, 52(2): 524-537. https://doi.org/10.2514/1.c032765

[16] Wang, C., Chang, S., Leng, M., Wu, H., Yang, B. (2016). A two-dimensional splashing model for investigating impingement characteristics of supercooled large droplets. International Journal of Multiphase Flow, 80: 131-149. https://doi.org/10.1016/j.ijmultiphaseflow.2015.12.005

[17] Patil, R.A., Sewatkar, C.M. (2024). Effect of thermal buoyancy on a fluid flow across six inline square heated cylinders. In Proceedings of the 26thNational and 4th International ISHMT-ASTFE Heat and Mass Transfer Conference December 17-20, 2021, IIT Madras, Chennai-600036, Tamil Nadu, India, pp. 195-201. https://doi.org/10.1615/ihmtc-2021.290

[18] Pal, J.S., Sapali, S.N., Ramakrishna, A.T. (2022). Exergy criteria of performance of waste heat recovery applied for the marine auxiliary boiler. International Journal of Heat and Technology, 40(1): 297-303. https://doi.org/10.18280/ijht.400135

[19] ANSYS Fluent Theory Guide, Release 14.5, 2016.