Design of Industrial Product with Curved Cavity Based on Lattice Boltzmann Method

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Received Mar. 1, 2025; Revised and Accepted Mar. 12, 2025

Abstract. This paper aims to explore the design method of curved cavity industrial products based on lattice Boltzmann method. Lattice Boltzmann method, as a mesoscale numerical simulation method, can effectively simulate complex fluid dynamics behavior and provide a new idea for the design of curved cavity. By constructing a reasonable lattice model and collision operator, the flow characteristics of the fluid in the curved cavity can be accurately described, and then the geometry and size parameters of the cavity can be optimized to meet the needs of specific industrial applications. Taking the triple-period minimal surface as an example, its application in the pneumatic soft linear driver shows that the design based on lattice Boltzmann method can realize the pure single-axis linear drive, with the performance of ”0 Poisson’s ratio”, large strain and strong load capacity. In addition, the method can also be used to predict the equivalent thermal conductivity of composite materials, which provides theoretical support for the application of curved cavity in thermal management and other fields. The research results show that the curved cavity design method based on lattice Boltzmann method has high accuracy and efficiency, and can provide strong technical support for the innovative design of industrial products, and has broad application prospects.

Keywords: Lattice Boltzmann method, Curved cavity, Industrial products.

1. Introduction

With the improvement of scientific and technological level and productivity, many advanced manufacturing technologies have emerged in the machinery and equipment manufacturing industry, such as electrolytic machining, laser processing, ultrasonic processing, plasma processing, EDM and so on. However, compared with the processing of the contour of the surface cavity, these technologies have more or less their own shortcomings, and can not be completely suitable for the processing of the surface cavity. In the last century, in the domestic CNC machine tools still belong to the high price, high-tech equipment period, for the processing of such parts is usually processed by copying machine tools. Nowadays, CNC machine tools in the domestic application is very common, the domestic universities and enterprises have also developed independent intellectual property rights of the CNC system [1,2], and has been promoted to the market, has been unanimously praised, and achieved good application results.

In modern industrial product design, curved cavity structure is widely used in aerospace, automobile manufacturing, electronic equipment, medical equipment and other fields because of its unique mechanical, thermal and fluid dynamics characteristics. For example, in the aerospace field, complex curved cavity structures are used to optimize aerodynamic performance and structural weight reduction of aircraft; In electronic devices, curved cavities can be used in thermal management modules to achieve efficient heat dissipation; In medical devices, curved cavity structures can be used to design implants or device enclosures that better fit the physiological structure of the human body. However, the design of curved cavity faces many challenges. Its complex geometry and internal flow field distribution make it difficult for traditional design methods to accurately predict and optimize its performance [3,4].

In recent years, Lattice Boltzmann Method (LBM), as a new computational fluid dynamics (CFD) method, has gradually attracted the attention of researchers. Based on the discrete lattice space and particle distribution function, the lattice Boltzmann method describes the macroscopic fluid motion by simulating the collision and transport process of microscopic particles. Compared with the traditional CFD method based on Navier-Stokes equations, the lattice Boltzmann method has the following significant advantages: First, it can naturally deal with complex boundary conditions and geometric shapes without complex mesh division, especially for the design of curved cavity with complex internal structure [5,6]; Secondly, the lattice Boltzmann method has higher accuracy and efficiency when dealing with complex physical phenomena such as multiphase flow, heat conduction and phase transition, and can more accurately simulate the flow and heat transfer process of fluid in curved cavity. In addition, lattice Boltzmann method has excellent parallel computing performance, which can effectively improve the computational efficiency of large-scale complex problems, and provide the possibility for rapid design and optimization of industrial products.

Although the lattice Boltzmann method has made remarkable progress in the field of fluid dynamics simulation, its application in the design of industrial products with curved cavities is still in the exploratory stage. At present, most research focuses on the development and numerical verification of theoretical models, while relatively few systematic studies have been conducted on actual industrial product design. For example, in the field of aerospace, although there are studies using lattice Boltzmann method to simulate the complex flow field of aircraft surface, how to translate these simulation results into specific design parameters and optimization schemes is still an urgent problem to be solved. In the field of electronic device thermal management, although the lattice Boltzmann method can effectively simulate heat flow distribution, there is no mature solution on how to combine the geometric design of curved cavity to achieve the best heat dissipation effect. In addition, for the optimization of mechanical properties of curved cavity, how to use lattice Boltzmann method to simulate the interaction between fluid and structure to achieve lightweight and high performance of structure is also one of the difficulties in current research [7].

In view of this, this study aims to explore the design method of curved cavity industrial products based on lattice Boltzmann method. Firstly, the basic theoretical framework of lattice Boltzmann method is elaborated, including the selection of lattice model, the design of collision operator and the processing of boundary conditions, which lays a theoretical foundation for the subsequent design application. Secondly, combined with specific industrial application scenarios, such as aerospace, electronic equipment and medical devices, through numerical simulation and experimental verification, the flow characteristics, heat transfer mechanism and mechanical response law of fluid in curved cavity are studied, and the quantitative relationship between fluid dynamics parameters and geometric parameters of curved cavity is established. Finally, based on the above research results, a set of systematic design methods and optimization processes are developed to realize the high-performance design of curved cavity industrial products. This study can not only enrich the application of lattice Boltzmann method in the field of industrial design, but also provide a new and efficient tool for the design of complex curved cavity structures, which has important theoretical significance and practical application value [8].

2. Boltzmann Method

The Lattice Boltzmann method was developed in the 1980s by MeNamaxa and Zaneltti by changing the real number operations in the Lattice Gas Automation (LGA) to integer operations. Some scholars have proposed a single relaxation model of lattice Boltzmann method, which greatly simplifies the complexity of LBM simulation and makes LBM easy to program, parallel operation, high computational efficiency and easy to simulate complex geometric boundaries, thus attracting wide attention from researchers [9].

The simulation process of lattice Boltzmann can be simply divided into collision and migration. The fluid mass in the simulation region is located on each grid node respectively, and the fluid is dispersed into a small microcluster. When the fluid flows, the fluid mass will only migrate in a fixed direction between the grid nodes. When the fluid in a fluid microcluster migrates to another node, it will collide with the fluid microcluster in that node, which is the migration collision process simulated by lattice Boltzmann.

Based on the discrete idea, fluid microclusters can only migrate along a fixed number of directions, and the migrated mass is distributed according to the discrete lattice Boltzmann equation. The migration and collision process of fluid microclusters can be expressed as follows:

$$f_\alpha(x + e_\alpha \Delta t, t + \Delta t) - f_\alpha(x,t) = -\frac{1}{\tau}[f_\alpha(x,t) - f_\alpha^{eq}(x,t)] + \Delta t S_\alpha(x,t). \quad (1)$$

Where Δt is time interval, its unit is lattice time. x is the position vector. e_α is the lattice velocity vector. α is the subscript of the velocity direction. S_α is the external force in the direction exerted on the fluid microclusters during the collision. τ is the relaxation time. f_α is the distribution function of microclusters in the α direction. f_α^{eq} is the equilibrium distribution function of the microcluster in the α direction.

Taking the D2Q9 model (a two-dimensional model with nine velocity components) as an example, where α is the number 0 to 8 representing eight fixed directional components as shown in figure 1. e_α can be calculated from equation (2):

$$e_\alpha = c(\cos[(\alpha - 1)\frac{\pi}{2}], \sin[(\alpha - 1)\frac{\pi}{2}]). \quad (2)$$

Where c is the lattice speed, which can be calculated from equation (3):

$$c = \Delta x / \Delta t = 1. \quad (3)$$

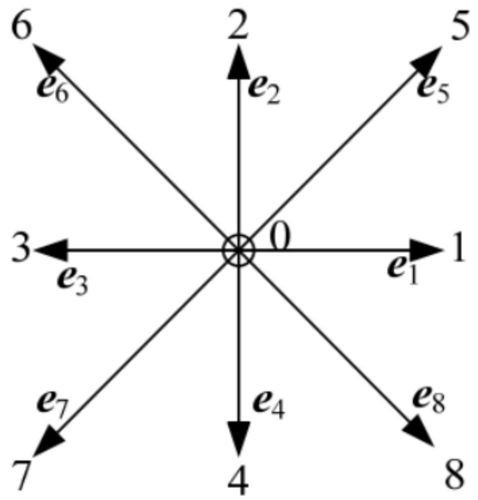

Fig. 1. D2Q9 model lattice velocity discrete mode

2.1. Theoretical Derivation of Lattice Boltzmann Method

The lattice Boltzmann method is derived from the Boltzmann equation used to describe the spatio-temporal variation of the particle velocity distribution function f in the theory of gas dynamics. Its derivation must first satisfy the following four simplifying assumptions [10].

1. Only two-body collisions between particles are considered, and three-body collisions or more than three-body collisions do not exist, and the collision adopts the steel ball model.
2. Particles are incoherent before collision, that is, molecular chaos hypothesis.
3. Ignoring the influence of external force on local collision.
4. The variation of the distribution function is caused by particle motion and particle collision.

The gas molecules in the control unit $dV = [r, r + dr]$ in the gas system are considered, and the gas microclusters are assumed to be acted on by an external force $F = ma$. At time t, the number of molecules $dN = f(r, \xi, t)d\xi dr$ with velocity located at $[\xi, \xi + d\xi]$. After time dt, if there is no collision between molecules, the position of these molecules becomes $r' = r + E\xi dt$ and the velocity becomes $\xi' = \xi + adt$. The number of molecules in the two state space elements is the same, that is:

$$f(r + \xi dt, \xi + adt, t + dt)d\xi dr = f(r, \xi, t)d\xi dr. \tag{4}$$

Where r is the spatial position vector of a molecular microcluster. ξ is the velocity vector of the molecule. a is acceleration.

In order to describe the change of molecular motion velocity and path in gas microclusters caused by intermolecular collision, the concept of collision operator $\Omega(f)$ is introduced to simply replace the collision term, and Boltzmann equation is obtained, as shown in equation (5):

$$\frac{\partial f}{\partial t} + \xi \frac{\partial f}{\partial r} + a \frac{\partial f}{\partial \xi} = \Omega(f). \tag{5}$$

Since the collision operator between gas microclusters is usually a complex integral term of the velocity distribution function f concerning the space position and velocity, equation (5) becomes a very complex differential integral equation, and the distribution function f is difficult to solve directly under normal circumstances. In order to further simplify the collision operator, Boltzmann equation can be applied to the solution of practical problems [11].

When the adjacent lattice points are in phase, the long-range force is cohesion, and when the adjacent lattice points are not in phase, the long-range force is adsorption. By applying external force in this way, the velocity of each lattice point in the simulation process of LBM is changed, and the velocity difference of each lattice point further changes the mass exchange during the collision and migration of microclusters at each lattice point, so that the gas-liquid two-phase separation is realized on a macro level, and LBM can simulate the coexistence of gas-liquid two phases.

When considering the problem of liquid infiltration, in addition to the necessary coexistence of gas-liquid two phases, it is necessary to introduce the force of solid on the gas-liquid two phases to supplement the solid-liquid surface tension and solid-gas surface tension, so as to realize the young equation. The expression of this force is shown in Formula (6):

$$F_{ads}(x,t) = -G_{ads}\varphi(x,t)\sum_{\alpha=1}^{8} w_\alpha s(x + e_\alpha \Delta t, t)e_\alpha. \tag{6}$$

Where G_{ads} is the adsorption constant; s is a switching function. When adjacent grids are solid boundaries, $s = 1$. That is, only when the gas phase and the liquid phase contact the solid surface, the attraction of the solid to the fluid will be generated. As a solid boundary lattice point, it does not participate in the process of migration collision [12].

The value of G_{ads} is plotted with the static contact angle θ between the droplet and the solid wall measured in the corresponding simulation results as shown in figure 2.

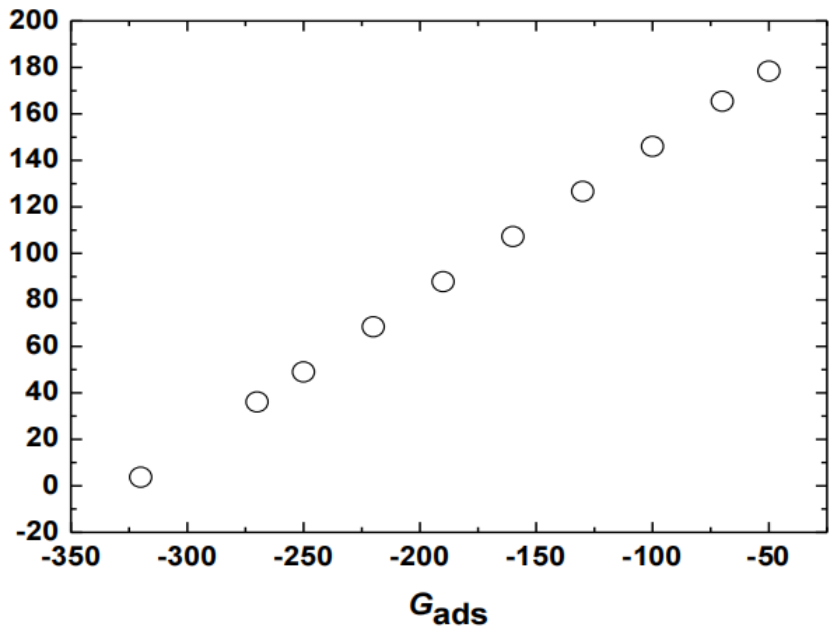

Fig. 2. Relationship between G_{ads} value and contact angle

The relationship between the static contact Angle θ of the droplet on the solid wall and the value of G_{ads} can be obtained by fitting each point in the figure, as shown in equation (7).

$$\theta = 210.75 + 0.647G_{ads}. \tag{7}$$

Based on the introduction of long-range forces between microclusters and the forces between solid and liquid microclusters and gas microclusters, the lattice Boltzmann method can solve the problem of multiphase flow involving two phases of gas and liquid.

2.2. Semi-finished Boring

After rough boring, semi-fine boring can be divided into two parts: R61.24 and R42.86 arc of the inner wall of the wine glass; Arc of glass bottom R17.22; The boring tool used for the two sections of the circular arc machining on the inner wall of the wine glass and the boring tool for the bottom of the wine glass can be the same tool, and different boring tools can also be used to process the profile. However, in order to improve the rigidity of the tool and ensure the outline size of the workpiece, the two parts are boring respectively [13].

(1) Boring the circular outline of the inner wall of the glass.

Boring the circular outline of the inner wall of the wine glass needs to layer the processing allowance and complete the processing by multiple cutting tools. Through the computer CAD software drawing analysis, through the cup mouth point to do an arc tangent line, can measure the tangent line and the axis of the Angle between the Angle, can be obtained processing the glass inner wall of the boring tool of the minimum value of the secondary declination is Kr=29. If the sub-declination Angle is less than the calculated Angle, the internal contour curve will cause the partial contour line of the starting point of the arc to interfere with the tool, and the internal contour curve obtained by the processing is incomplete, and the arc size is enlarged by the processing, and the correct contour shape cannot be formed.

(2) Boring glass bottom arc profile.

When boring the arc profile of the bottom of the glass, the main consideration is to avoid the interference of the tool; Interference with the tool when cutting a small radius dimension profile feed. A layer-by-layer machining allowance can be used to finally leave a margin for finishing. The boring tool of the bottom of the glass is mainly affected by the cone hole after drilling by the drill, and the Angle of the cone hole directly affects whether the tip of the boring tool can be processed to the center of the workpiece and whether the circular arc size of the bottom of the glass can be formed. According to the known size of the twist bit, the Angle size of the taper hole is $118°$. It can be seen that the knife Angle of the boring tool cannot be greater than $59°$, and the main and secondary declination angles are $90°$ and $31°$. When boring the radius of the inner wall of the wine glass, some processing allowance is left for finishing, in order to improve the processing quality and surface quality [14,15].

(3) Fine boring machining.

Fine boring processing can be divided into two forms and methods: one is in the semi-finishing when processing two parts of the arc, semi-finishing immediately completed finishing; The other is that if the overall consistency of the arc profile is high, it is necessary to replace a boring tool to meet the requirements of the circular arc at both ends of the inner wall profile and the circular arc at the bottom of the glass, and will not form tool processing interference and so on.

3. Conclusion

In today's complex and changeable industrial product design field, the demand for product design with complex curved cavity structure is increasing. This study focuses on the application of lattice Boltzmann method (LBM) to the design of curved cavity industrial products, aiming to explore an efficient, accurate and innovative design path. Through in-depth research and practice, the following important results and conclusions have been obtained.

Lattice Boltzmann method, as a mesoscopic dynamic model, has been successfully introduced into the design of curved cavity products with its unique advantages in the fields of fluid mechanics and heat conduction. By constructing a discrete lattice system adapted to the complex geometric characteristics of curved cavity, physical processes such as fluid flow and heat transfer in the cavity can be simulated from the point of view of the movement of microscopic particles. This simulation method based on microscopic dynamics breaks through the limitations of traditional design methods in dealing with complex geometric and physical coupling problems, and provides a new theoretical basis for the optimal design of curved cavity products. At the same time, combined with the traditional numerical simulation methods such as computational fluid dynamics (CFD), the multi-method collaborative optimization is realized, giving full play to their respective advantages, and further improving the design accuracy and efficiency.

In the actual case of curved cavity product design, the design process based on lattice Boltzmann method can accurately predict key physical quantities such as flow field distribution and temperature field change in the cavity. Through the analysis and processing of a large number of simulation data, we can clearly identify the flow dead Angle, thermal resistance area and other key parts that affect the performance of the product, which provides a strong basis for targeted structural optimization. Compared with traditional design methods, the design method based on LBM can significantly shorten the design cycle, reduce the number of design iterations and reduce the design cost while ensuring the design accuracy. This is particularly important in the design of complex curved cavity products, because the geometric structure of such products is complex, and the traditional method often needs a lot of experimental verification and repeated modification, while the LBM-based method can quickly evaluate multiple design schemes in the virtual environment and screen out the best scheme in advance, thus accelerating the transformation process of products from conceptual design to actual production.

With the help of the lattice Boltzmann method, the performance of the curved cavity product is significantly optimized. For example, in the design of curved cavity products of heat exchangers, the flow path structure inside the cavity is optimized to make the fluid flow in the cavity more smooth, enhance the heat exchange efficiency, and reduce the pressure drop loss. In the design of complex curved cavity parts in the aerospace field, the flow field and stress distribution simulated by LBM are used to carry out lightweight design of the structure, which reduces the weight of the parts and improves the overall performance of the product on the premise of ensuring the strength of the structure. In addition, the design method based on LBM also provides the possibility for the functional expansion of products. Through the in-depth understanding and regulation of the internal physical process of the cavity, new curved cavity products with special functions can be developed, such as the fluid conveying cavity with self-cleaning function and the thermal management cavity with intelligent temperature control function. It has injected new vitality and innovative elements into industrial product design. The design method of industrial product with curved cavity based on lattice Boltzmann method has broad application prospect. With the continuous development of computer technology, the computational efficiency of LBM will be further improved, and it can deal with more complex curved cavity structures and multi-physical field coupling problems. In the automotive industry, it can be used for the design optimization of complex curved cavity components such as engine cooling system and fuel injection system. In the field of electronic equipment manufacturing, it can carry out high-performance design for electronic chip cooling cavity and micro-sensor sealing cavity. In the medical device industry, it can be applied to the internal fluid dynamics and thermodynamic optimization design of implantable medical devices such as artificial joints and cardiac pacemakers to improve the biocompatibility and functionality of products. The popularization of this design method will help to enhance the competitiveness of products in various industrial fields and promote the technological progress and innovative development of related industries.

In summary, the curved cavity industrial product design method based on lattice Boltzmann method is an innovative, efficient and practical design method. It not only provides a new perspective and method framework for the design of complex curved cavity products in theoretical research, but also shows significant performance optimization effect and cost benefit advantages in practical application. With the continuous improvement and promotion of the technology, this method is expected to become an important technical support in the field of industrial product design in the future, and open up a new way for the high-performance design and innovative development of complex industrial products.

4. Conflict of Interest

The authors declare that there are no conflict of interests, we do not have any possible conflicts of interest.

Acknowledgments. This work was supported by the Key Scientific Research Project of Henan Provincial Universities in 2024 (24B110020) from Henan Provincial Department of Education. Project Category: Basic Research Program. Project Name: Research on design method of Curved cavity industrial products based on lattice Boltzmann method.

References

1. Weng L J, Rahmani A, Sajadi S M, et al. Simulation of natural convection of nanofluid inside a square cavity using experimental data by lattice Boltzmann method[J]. Ain Shams Engineering Journal, 2024, 15(5): 102711.
2. Ahmed S Y, Al-Amir Q R, Hamzah H K, et al. Investigation of natural convection and entropy generation of non-Newtonian flow in molten polymer-filled odd-shaped cavities using finite difference lattice Boltzmann method[J]. Numerical Heat Transfer, Part B: Fundamentals, 2024: 1-26.
3. Tiribocchi A, Durve M, Lauricella M, et al. Lattice Boltzmann methods for soft flowing matter[J]. arXiv preprint arXiv:2405.14551, 2024.
4. Liu L, Meng Z, Zhang Y, et al. Three-Dimensional Modeling of Non-Newtonian Fluids Flow in the Mixing Section of Extruder Using the Two-Relaxation-Time Lattice Boltzmann Method[J]. Industrial & Engineering Chemistry Research, 2025.
5. Channouf S, Jami M. Impact dynamics of droplets on circular bodies: Exploring the influence of wettability, viscosity, and body dimensions using the lattice Boltzmann method[J]. Physics of Fluids, 2024, 36(5).
6. Samanta R, Chattopadhyay H. Study of thermal convection in liquid metal using modified lattice Boltzmann method[J]. International Journal of Numerical Methods for Heat & Fluid Flow, 2025.
7. Fang J, Liu X, Wang T, et al. Micro lubrication and heat transfer in wedge-shaped channel slider with convex surface texture based on lattice Boltzmann method[J]. Nanomaterials, 2024, 14(3): 295.
8. Zhang W, Sun D, Chen W, et al. Lattice Boltzmann modeling of convective heat and solute transfer in additive manufacturing of multi-component alloys[J]. Additive Manufacturing, 2024, 84: 104089.
9. Zhao C, Jin Y, Fan C, et al. Numerical investigation of fluid flow behavior in steel cord with lattice Boltzmann methodology: The impacts of microstructure and loading force[J]. Plos one, 2024, 19(5): e0301142.
10. Bukreev F, Kummerl nder A, Jeberger J, et al. Benchmark Simulation of Laminar Reactive Micromixing Using Lattice Boltzmann Methods[J]. AIAA Journal, 2024: 1-10.
11. Samanta R, Chattopadhyay H, Guha C. Corner melting in low Pr metals: A study using lattice Boltzmann method[J]. Numerical Heat Transfer, Part A: Applications, 2024: 1-31.
12. Fanaee S A, Shahriari A, Nikpour S. The Lattice Boltzmann Simulation of Free Convection Heat Transfer of a Carbon-Nanotube Nanofluid in a Triangular Cavity with a Solar Heater[J]. Journal of Nanofluids, 2024, 13(3): 694-709.
13. Haddach A, Smaoui H, Radi B. The study of coastal flows based on lattice Boltzmann method: application Oualidia lagoon[J]. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 2024, 46(4): 225.

14. Biswas R, Sohel N, Taher M A. Comparative study to analyze the overall performance of upstream and downstream wedge ribs microchannels using thermal lattice Boltzmann method[J]. Journal of Engineering and Applied Science, 2024, 71(1): 228.
15. Gao Z, Yang Y, Hu X, et al. Numerical investigation of thermal soak within engine bay using lattice Boltzmann method[J]. Scientific Reports, 2024, 14(1): 19472.

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