Analysis of Flow Resistance Characteristics in Shellfish Catchers Based on Porous Media Model and Surrogate Model

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Full Text

Preamble

Analysis of Flow Resistance Characteristics in Shellfish Catchers Based on Porous Media Model and Surrogate Model Dingsheng Xie a, Yu Xin a, Cong Yang b, Jingwen Zhang a，Xu Han c, Pengfei Zonga，Chaoyong Zonga*

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Abstract

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Keywords

Shellfish Catchers; Flow Resistance Analysis; Porous Media Model; Surrogate Model

1 Introduction

The Shellfish Catchers (SC), a critical component installed within the tertiary circuit of the nuclear power system, is designed to intercept and filter out impurities such as shellfish and seaweed from the seawater. Its primary function is to safeguard the operational integrity of the cooling circulation loop. A schematic diagram of the system is provided in Figure 1 [Figure 1: see original paper] [1,2]. Flow resistance is a critical performance characteristic of the SC. Excessive flow resistance can lead to insufficient cooling water supply, potentially resulting in system overheating and serious safety hazards. However, the complex turbulent flow conditions and the dynamic changes in the porosity of the filter screen are the key factors complicating the accurate analysis of its flow resistance properties [3]. Therefore, a thorough investigation into the flow resistance characteristics and the underlying influence mechanisms of the SC is of significant engineering importance for enhancing the operational reliability and safety margin of nuclear cooling systems. [4].

Current methodologies for investigating flow resistance characteristics primarily include analytical methods, experimental techniques, and Computational Fluid

Dynamics (CFD). The analytical approach rests on theoretical derivation and mathematical calculations to predict flow resistance, often relying on simplified assumptions, with its core being the solution of the Navier-Stokes equations. For simple laminar models such as Poiseuille and Couette flow, these equations can be solved directly to yield accurate solutions. However, the applicability of this method is severely limited, as it fails to handle turbulent flows and complex geometries with sufficient precision. [5,6]. Thus, engineering practice often resorts to empirical and semi-empirical formulas. A key drawback of these formulas is their dependence on empirical coefficients, which must be obtained through targeted experimentation. This reliance poses a significant constraint on their general applicability [7]. Consequently, researchers have turned to experimental methods to analyze flow resistance. Although experimentation can yield direct and reliable data, it is often hampered by high costs, prolonged durations, and potential measurement inaccuracies. Furthermore, conducting experiments under extreme operating conditions presents significant challenges, which hinders comprehensive flow resistance analysis [8,9]. The recent rapid development of Computational Fluid Dynamics (CFD), coupled with its strengths in accurately simulating turbulent flows, low computational cost, and absence of physical limitations, has established it as the preferred method for flow resistance analysis among many scholars.

This adoption has thereby established a robust foundation for high-fidelity research on the SC' s flow resistance properties [10–12]. Nevertheless, the numerical discretization of the SC' s filter mesh is confronted by a cross-scale problem. Direct modeling approaches are often hampered by exorbitant computational demands, creating a formidable obstacle for the mechanistic analysis and predictive assessment of flow resistance in engineering design. Therefore, the exploration of highly efficient and accurate modeling methodologies for SC flow resistance is of paramount importance for advancing the safety and reliability of nuclear power cooling systems.

To circumvent the challenges associated with modeling the intricate filter screen, many researchers have turned to the

Porous Media Model (PMM) as a reduced-order approach. This method streamlines the complex three-dimensional geometry and has been extensively employed for the prediction and analysis of fluid flow characteristics [13,14]. The application of PMM is well-established across various fields. For instance, Vu et al. [15] developed an extended Boussinesq model that accounts for both the inertial and viscous resistance coefficients of porous media to predict wave propagation.

Similarly, Zong et al. [16] employed a PMM to simulate the blocking effect of flame-retardant sheets within an explosion-proof safety valve. Wood et al. [17] reviewed the performance of various turbulence models for simulating internal flow fields in porous media, providing a valuable reference for future applications. Hilfer et al. [18] analyzed the connectivity of porous structures based on permeability and validated models for mass, volume, and momentum transport.

In a different approach, Basser et al. [19] used an incompressible smoothed particle hydrodynamics (SPH) scheme to simulate fluid seepage, reporting general agreement with experimental data. To investigate fluid transport, Chen et al. [20]

introduced an asymmetry factor, deriving a generalized optimization theory for asymmetric branching flows to determine the optimal radius ratio for minimal flow resistance. Gorgun et al. [21] conducted CFD simulations to analyze the relationships between the flow resistance coefficient, pressure, and porous media thickness, with experimental results confirming good model accuracy. Finally, Hu et al. [22] proposed a five-sphere model to elucidate the mechanism of flow resistance, deriving an empirical parameter-free formula for viscous resistance, which was experimentally validated to be the dominant loss contributor.

To further analyze previous research on the flow resistance characteristics of porous media, a literature survey was conducted. The findings can be summarized into the following: While flow resistance analysis in nuclear cooling systems has been extensively applied to components like valves and pipes, research focusing on the SC using CFD remains relatively scarce. Although CFD is a potent tool for characterizing the flow resistance of the SC, the computational cost associated with directly resolving its complex 3D filter screen geometry is often prohibitive. To mitigate this, the PMM, recognized for its efficiency in predicting pressure drop, offers a viable approach for simplifying the SC model. However, the specific application of PMM to replace the detailed 3D orifice plate filter screen is not widely documented in open literature. A critical step in this methodology is the calibration of the viscous resistance coefficient, which is pivotal for accurately representing the filter screen. Typically, this calibration is performed for a single operating condition. This practice, however, may not ensure model fidelity across a broader range of complex operational scenarios, potentially leading to inaccurate pressure drop predictions under off-design conditions. The literature currently provides limited discussion on this specific limitation and strategies for its mitigation.

This study investigates the flow resistance characteristics of the SC through numerical modeling and surrogate model-based prediction. For the dynamic analysis, a reduced-order CFD model based on the PMM was developed and validated against the detailed filter screen model (FSM), which had been previously verified through experiments on a

custom-built test rig. This methodology offers a valuable reference for the development of analogous structural models.

Furthermore, a Design of Experiments (DOE) was implemented using this reduced-order model to generate simulation data for training a surrogate model. This approach significantly reduces the computational cost and time required for flow resistance prediction. The main contributions of this work are as follows: (1) development of a reduced-order CFD model for the SC; and (2) predictive analysis of the SC' s flow resistance characteristics using a surrogate model. These aspects are discussed comprehensively in this paper. 2 Fundamental Principles and Composition of the SC As shown in Figure 2 [Figure 2: see original paper], the SC consists of several key components: the shell, a backwashing device, an electric motor, and the filter. The seawater inlet is located at the bottom, with the outlet on the left. The filter screen, installed centrally, features a conical design to optimize the flow area and facilitate cleaning. The backwashing unit connects to a drainpipe that

vents to a low-pressure zone. When activated, it induces a reverse flow of seawater that back-flushes the filter, dislodging contaminants and expelling them through the drainpipe to improve porosity. The electric motor provides the motive force to rotate the backwashing device, thereby enabling complete cleaning of the filter mesh.

3. Fundamental Principles of PMM The FSM in the SC, characterized by an area of 1.35 m^2 and 3-mm diameter pores, presents a formidable challenge for computational modeling. Directly constructing and meshing this detailed geometry requires immense computational power.

The need for a refined mesh around the pores to capture the flow accurately further leads to long simulation times and high

costs, making comprehensive pressure-drop analysis impractical. To circumvent the issues of model complexity and computational inefficiency, a PMM is utilized as a substitute for the detailed filter screen. This technique simplifies the problem by modeling the porous structure not by its exact geometry, but through its macroscopic hydrodynamic resistance, implemented via additional source terms in the momentum conservation equations. This avoids the explicit simulation of flow within every individual pore.

3.1 Fundamental Principles

Flow in a porous media region is modeled by adding a momentum source term to the standard Navier-Stokes equations.

This source term comprises both viscous and inertial resistance components, as given by Equation (1): è j =1

where S i is the source term for the momentum equation in the i-th (x, y,

z) direction; | v | is the velocity magnitude;

D and C are prescribed coefficient matrices. The term with coefficient Dij represents the viscosity resistance coefficient, which models the pressure drop due to fluid viscosity at low speeds (laminar flow) and is proportional to velocity. The term with coefficient Cij represents the inertial loss, which models the pressure drop caused by inertial forces at high speeds (turbulent flow) and is proportional to the square of the velocity. Given the relatively low flow velocity within the SC, the inertial loss term can be neglected. By incorporating Darcy's law, which describes the volumetric flow rate through a porous medium under low-velocity, laminar conditions, the model can be simplified as shown in Equation (2):

where q is the Darcy velocity; K is the permeability tensor; m is the dynamic viscosity of the fluid; and Ñp is the pressure gradient.

By combining the mass conservation equation with Darcy' s law, the governing equation for single-phase flow is derived, as shown in Equation (3):

- Ñ × (r

q) = Q

where f is the porosity; r is the fluid density; and Q is the source term. Assuming the compressibility of seawater is negligible at low flow velocities, implying r is treated as a constant, Equation (3) can be simplified to Equation (4):

Ñ×q = Q

The pressure drop that Ansys Fluent computes in each of the three (x, y,

z) coordinate directions within the porous region is Equation (5):

v j Dnx j =1 a xj

Dpx = å

v j Dn y j =1 a yj

Dp y = å

v j Dnz j =1 a zj

Dpz = å where 1 / a

are the entries in the matrix D in Equation 1, v are the velocity components in the x, y, and z

directions, and D n x , Dn y , and Dnz are the thicknesses of the medium in the x, y, and z directions.

3.2 Modification of the PMM

To enhance the viability of using the PMM as a substitute for the orifice plate model (OPM), modifications are

required to better capture the authentic behavior of the fluid flow through the porous structure. These refinements are achieved by adjusting the geometric and physical parameters within the governing equations. Given that temperature variations and turbulence effects in the seawater medium are neglected, corrections pertaining to the energy equation and turbulence models are not considered. The modification based on the continuity equation is detailed as follows:

¶ (fr) + Ñ × (fr v) = 0

where r is the fluid density; v is the superficial velocity, calculated based on the total cross-sectional area of the porous medium. The relationship between the intrinsic velocity v and the superficial velocity v real is defined as:

v real = v / f

4. Flowchart of the pressure drop predictive model for the SC Considering the difficulty of constructing the FSM of the SC and the high cost of pressure drop simulation, this study uses an OPM to represent local pressure drop as an equivalent to the overall screen pressure drop. The procedure for developing the pressure drop prediction model of the SC is as follows: The OPM and PMM are simulated, and their pressure drop results are compared. The Dij is iteratively adjusted until the PMM can effectively fit the OPM. When the pressure drop error between the two models is less than 5%, the Dij is taken as valid. During this process, the OPM is experimentally verified to ensure simulation accuracy. The obtained valid Dij is then transferred to the PMM of the SC.

Under the same porosity as the OPM-based FSM, the pressure drop difference between the SC' s FSM and the PMM is compared. When the error is less than 10%, the data can be used as effective training data. DOE is performed on the boundary conditions of the above process. The data base of porosity(f), flow rate (Qv), pressure drop (DP)and Dij is obtained through repeated iterative calculations, and the final pressure drop prediction model is obtained after surrogate

model training. The flowchart of the pressure drop prediction model for the SC is shown in Figure 3 [Figure 3: see original paper].

4.1 Calibration of the Viscous Resistance Coefficient To ensure a fully developed flow profile for accurate pressure drop analysis across the screen, the fluid domains both upstream and downstream of the OPM and the PMM are extended. The diameter of the orifice in the OPM is 50 mm. The specific configuration of this comparative model is illustrated in Figure 4 [Figure 4: see original paper].

Taking the common operating conditions of the SC as an example, the OPM was adjusted based on the flow rate per unit area. The specific boundary condition parameters are listed in Table 1 . A pressure monitoring line was set at the center of the OPM, and the corresponding pressure contour from the simulation is presented in Figure 5 [Figure 5: see original paper].

The results demonstrate that an appropriately calibrated viscous resistance coefficient ensures an excellent fit between the OPM and the PMM. This agreement is observed both in the region from the inlet to the fitting zone, and in the region from 5D downstream of the fitting zone to the outlet. The comparative results are shown in Figure 6 [Figure 6: see original paper].

Total Area

1350000.0 mm2

2827.4 mm2

2827.4 mm2

Porosity

Medium Density

1030 kg/m3

1030 kg/m3

1030 kg/m3

Operating Flow Rate

2800 m3/h

4.07 m3/h

4.07 m3/h

In summary, the PMM, through the calibration of the viscous resistance coefficient, accurately simulates the pressure drop across the OPM. This validated model provides a foundation for further analysis of the flow rate versus pressure drop characteristics of the SC.

To verify the effectiveness of the OPM pressure drop simulation, this study designed five OPM with different porosity levels, with flange specification DN50/PN10, as shown in Figure 7 [Figure 7: see original paper]. In addition, a water medium pressure drop test loop with DN50 specification was constructed, as shown in Figure 8 [Figure 8: see original paper]. The specifications of the sensors selected for the

experimental setup are presented in Table 2 .

Model

Measuring Range

Precision

JVMO-2088X

0.00~1.00 MPa

0.1% F.S.

JVMO-2088X

0.00~1.00 MPa

0.1% F.S.

Flow Sensor

CMF9025

0-200 L/min

1.00% F.S.

DAQ Chassis

cDAQ-9185

4-slot USB

Current Acquisition Card

NI-9208

4-20mA，16-bit，200kS/s，32channels

Pressure Sensor Sensor

Acquisition Card

Sampling Frequency

2000 Hz

In the experiment, the outlet pressure of the pump was controlled, and the flow rate in the test pipeline was measured in real time using a flow sensor. When the flow rate stabilized at the operating flow rate, the pump outlet pressure was held

constant, and the pressure drop at that moment was recorded using two pressure sensors. The pressure drops across OPMs with different porosity levels were measured and compared with simulation results, as shown in Figure 9 [Figure 9: see original paper]. The results indicate that the relative error between the experiment and simulation is small. The OPM simulation model exhibits high accuracy and can effectively fit the actual pressure drop behavior of the OPM.

4.2 Solution for the Flow Resistance Characteristics of the SC The filter screen within the SC was modeled using the porous media theory. By applying a properly calibrated viscous resistance coefficient, the flow rate versus pressure drop relationship for the SC was determined. This methodology was subsequently employed to simulate a wide range of operating conditions, thereby generating comprehensive pressure drop curves for the device.

To validate the applicability of the PMM in representing the SC' s filter, a comparative analysis was first conducted at a porosity of 35%. The detailed FSM and the equivalent PMM were simulated under identical conditions, and the resultant

error between the two was analyzed. The numerical procedure for the SC model involved extracting the fluid computational domain, mesh generation, setting boundary conditions, and configuring the solver parameters. To enhance computational efficiency, a symmetric half 3D model of the computational domain was adopted for the simulations. The computational mesh for this domain is illustrated in Figure 10 [Figure 10: see original paper].

To ensure simulation accuracy and convergence, the fluid domains at the inlet and outlet of the valve were extended by 3 and 10 times the valve diameter, respectively. This allows the flow to become fully developed. Furthermore, to maintain consistency in the pressure drop calculation methodology, the pressure monitoring surfaces were defined at the SC inlet and at a location 5 diameters downstream from the outlet, as specified in Figure 11 [Figure 11: see original paper].

To mitigate the influence of mesh discretization on simulation accuracy, a grid independence study was conducted using four distinct grid resolutions. The pressure drop across the monitoring surfaces and the maximum velocity within the computational domain were selected as reference metrics for the assessment. The results of the grid independence study for the PMM and the detailed FSM are presented in Figures 12(a) and 12(b), respectively. Comparison of the mesh element count between the PMM and the FSM in Figures 13.

(a) Grid independence verification for the PMM

(b) Grid independence verification for the FSM

Considering both computational accuracy and cost, the 'Very Fine' grid level was selected as the final mesh, as shown in Figure 14 [Figure 14: see original paper].

For the detailed FSM, the boundary condition at the inlet was set to a flow rate of 1400 m^3/h. For the porous media simulation, the inlet boundary was identically set to 1400 m^3/h, with the porosity and viscous resistance coefficient specified as 35% and 9.12$×10^{8}$, respectively. Additionally, key solver parameters for the CFD simulations were configured as summarized in Table 3 .

Category

Setting

Solver

Absolute velocity formulation

Pressure-based, steady 1/2 3-D Solution Method

SIMPLE scheme

Spatial Discretization Scheme

Second Order Upwind

Convergence Criterion

< 1e-4

Turbulence Model

Realizable k - w

Near-Wall Treatment

Standard Wall Functions

4.3 Comparison of Results

A comparative analysis was conducted on both the detailed FSM and the PMM at 35% porosity and a flow rate of 2800

m^3/h. The results demonstrate that the porous medium model can significantly reduce the flow resistance calculation time for shellfish catchers, with a computational cost reduction of 79.4%. Additionally, the results from the filter screen model and the porous medium model show minor discrepancies, with the pressure drop calculated by the PMM being 3%-6% higher than that of the FSM. This close agreement validates the feasibility of using the PMM as a viable substitute for the filter screen in simulations. A comparison of the pressure and velocity fields is presented in Figure 15 [Figure 15: see original paper], and the quantitative results are contrasted in Figure 16 [Figure 16: see original paper].

(a) Velocity contour of the PMM

(b) Velocity contour of the FSM

(c) Pressure contour of the PMM

(d) Pressure contour of the FSM

The calculated curves of flow rate versus viscous resistance coefficient for the SC at different porosity levels are presented in Figure 17 [Figure 17: see original paper]. Analysis of these curves reveals that the viscous resistance coefficient reaches its minimum at a flow

rate of 1500 m^3/h and its maximum at 6500 m^3/h. Furthermore, the coefficient is highest at a porosity of 25% and lowest at 85%. Based on this data, the following specific conclusions can be drawn: (1) The viscous resistance coefficient of the filter screen increases linearly with the flow rate. (2) The viscous resistance coefficient increases exponentially as the porosity decreases.

A comparative analysis of the flow rate–pressure drop curves across various porosity levels reveals a nonlinear, quadratic relationship between the flow rate and the pressure drop in the SC. For a given porosity, the pressure drop is minimal at a flow rate of 1500 m^3/h and maximal at 6500 m^3/h. Conversely, at a constant flow rate, the pressure drop is lowest for the filter screen with 85% porosity. Based on these findings, the following conclusions are drawn: (1) For a filter screen with constant porosity, the pressure drop across the SC increases with the flow rate, following a quadratic correlation. (2) For a constant flow rate through the SC, the pressure drop decreases as the filter porosity increases, as detailed in Figure

5.1 Construction of the Surrogate Model

To further reduce the cost of predicting the flow resistance characteristics of the SC, this study developed surrogate models for its key parameters. The construction process began with a dataset of 357 simulation samples. Using porosity and flow rate as input variables, and the viscous resistance coefficient and pressure drop as output responses, five distinct surrogate modeling techniques were employed to establish the mapping relationships. These techniques were: Kriging (KRG), Radial Basis Function (RBF), Support Vector Regression (SVR), Polynomial Response Surface (PRS), and Artificial Neural Network (ANN). The dataset was partitioned, with 80% allocated for training and 20% reserved for testing.

The kernel functions used for the respective surrogate models are listed in Table 4 .

Model

Correlation function

bˆ = (F T R -1F) -1 F T R -1Y

R[z (xi), z (x j)] = exp ç -åqk | xik - x kj |2 ÷ è k =1

b0 + å bi xi + åå bij xi x j + ååå bijk xi x j xk

i =1 j =1

å lf (r(x , x))

c = 1.0

æ ‖ x - x‖ k (x , x ¢) = exp ç ÷ s = 2.0 2s 2 ø

å (a - a)k (x ×

x) • b

i =1 j =1 k =1

f (å wi xi - q)

To effectively evaluate the accuracy of the surrogate models, the correlation coefficient (R^2), Mean Squared Error (MSE), Root Mean Squared Error (RMSE), and Mean Absolute Percentage Error (MAPE) were selected as the performance metrics. Their corresponding mathematical expressions are provided in Table 5 .

Mathematical Expression

å (y - yˆ)

R 2 = 1 - i =n1

å(y - y)

å (yi - yˆ i) n i =1

MSE =

RMSE =

æ y - yˆ i ö MAPE = max ç i è yi ø

(yi - yˆ i) n i =1

5.2 Analysis Results of the Surrogate Model The accuracy assessment of the surrogate models developed using different methods indicates that all models perform satisfactorily in predicting the SC' s flow resistance characteristics and viscous resistance coefficient. Regarding the prediction of flow resistance, all five surrogate models achieved correlation coefficients (R^2) exceeding

0.
1. Among them, the ANN, RBF, and KRG models demonstrated superior performance, with their Mean Absolute Percentage Error (MAPE) all below 1.5%, which is lower than that of the PRS and SVR models. For predicting the viscous resistance coefficient, the RBF and ANN models showed commendable accuracy, characterized by high correlation coefficients and low prediction errors, with ANN emerging as the most accurate predictor.

In summary, the analysis conclusively shows that the Artificial Neural Network (ANN) method is the most effective for predicting both the flow resistance characteristics and the viscous resistance coefficient of the SC. It enables the rapid prediction of the SC' s flow resistance while maintaining considerable predictive accuracy. The detailed comparative results are presented in Figure 19 [Figure 19: see original paper]. The prediction accuracy of the different models for both pressure drop and viscous resistance coefficient is shown in Figure 20 [Figure 20: see original paper].

(a) Comparison of pressure drop prediction

(b) Comparison of viscous resistance coefficient prediction

accuracy

accuracy

6 Conclusion

This study employed a porous media model to replace the detailed FSM of the SC and calculated its flow resistance characteristics using Computational Fluid Dynamics (CFD). Simulation data for flow resistance and the viscous resistance coefficient under varying flow rates and porosity conditions were compiled and used to train five surrogate models (ANN, KRG, RBF, SVR, and PRS) to enhance the predictive capability for the SC' s flow resistance. The main conclusions are summarized as follows: (1) Appropriate calibration of the viscous resistance coefficient in the porous media model effectively replicates the pressure drop of the orifice plate with the same porosity. Assigning this calibrated coefficient to the SC' s porous media model provides a reliable substitute for the detailed FSM at corresponding flow rates, with a computational error of less than 6%. Furthermore, the porous media model significantly reduces both the mesh count required for the SC CFD model

and the computational cost of determining flow resistance characteristics. (2) Establishing a mapping relationship among flow rate, porosity, pressure drop, and the viscous resistance coefficient based on surrogate models enables efficient prediction of the SC' s flow resistance. Among the models evaluated, the Artificial Neural Network (ANN) surrogate model performed the best, exhibiting higher correlation and lower prediction error.

This study represents an extension of research on the flow resistance characteristics of the SC. While it cannot encompass all scenarios encountered in industrial practice, it provides a valuable reference for simplifying similarly complex FSM. However, this work is subject to the following limitations: (1) Constraints in experimental conditions precluded direct experimental validation of the flow resistance analysis for the physical FSM. Although the turbulence model employed for the flow resistance analysis has been well-validated in other literature, the simplification via the porous media model was specifically developed for the SC' s filter screen. Consequently, its applicability to other types of porous media may be limited and requires further verification. (2) While the ANN surrogate model demonstrated effective prediction of the SC' s flow resistance characteristics, its predictive capability for other, more complex physical processes warrants further investigation. These limitations should be carefully addressed in future research.

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Replication of Results All research data has been incorporated into the charts presented in this paper.

Conflict of Interest The authors declare that they have no conflict of interest.

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Note: Figure translations are in progress. See original paper for figures.