

Parametric Study on the Effects of Side Slot Geometry on Vortex Dynamics in Hypervapotron Structure

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1. Introduction

Efficient heat removal under high heat flux conditions has become critical for advanced energy systems, which are required to withstand thermal loads of several MW/m². At these extreme fluxes, boiling near the heated wall generates large amounts of vapor, leading to a high void fraction condition. These conditions are particularly relevant for fusion reactor divertors and for the IVR-ERVC(In-Vessel Retention with External Reactor Vessel Cooling) strategy. Under such high void fraction conditions, bubble dynamics—coalescence and breakup—are critical, making heat transfer highly complex and unstable. To effectively remove the heat, it is crucial to facilitate vapor removal from the heated surface while ensuring a continuous liquid supply.

The hypervapotron is a structure with fins aligned perpendicular to the main flow, which enhances vapor ejection through its geometric configuration. Vortices generated by the hypervapotron create recirculating flows, a key part of the vapotron effect, promoting both vapor ejection and surface rewetting[1,2]. The vortices originate from shear layer instabilities caused by the velocity gradient. It has been shown in various studies that a quantitative analysis of vortex characteristics can be directly correlated with improved heat transfer performance.

Table 1. Previous studies on the quantitative correlation between vortex characteristics and heat transfer performance

Paper	Contents	Conclusion
McCroskey [3]	Temperature - Vorticity analogy theory and experimental validation	Good agreement in shear flows
Song and Wang [4]	Quantification of intensity through dimensionless number Se based on absolute vorticity flux	Consistent correlation between Se and Nu
Chang [5]	Quantification of flow intensity through span-averaged streamwise vorticity flux	Consistent correlation between vorticity flux and Nu
Lemenand [6]	Quantification of flow intensity through spanwise-averaged absolute streamwise vorticity flux	Consistent correlation between vorticity flux and Nu

Previous studies on hypervapotron have shown enhanced heat transfer performance compared to flat channels[1]. However, these studies have largely focused

on the overall performance without directly linking the specific design parameters to the fundamental vortex characteristics.

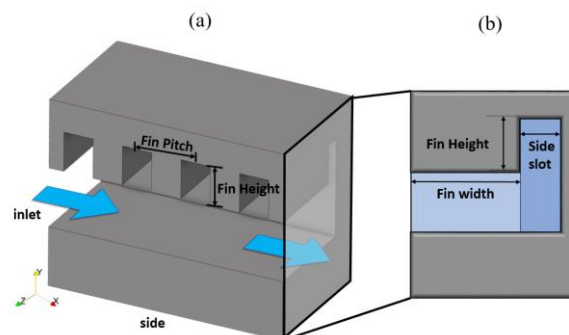


Fig. 1. Geometry of the hypervapotron cooling channel: (a) overall configuration and (b) side view

The side slot is a region at the end of the fin that provides an additional fluid path along the main flow direction. It is found that this path enhances vapor ejection and surface rewetting, improving cooling performance. Furthermore, velocity gradients between the fin and the side slot generate vortices, leading to asymmetric flow patterns[7,8]. However, since an increase in side slot width inherently reduces the fin width, the resulting shorter fins may allow the redirected flow through the side slot to diminish the intended hydrodynamic effects, thereby undermining their performance.

This study aims to perform a parametric investigation of side slot width to optimize hypervapotron structures, with a primary focus on quantitatively characterizing the vortex induced by these structures through single-phase simulations.

2. CFD Modeling

The present study employed OpenFOAM (V12) to perform the computational analyses.

2.1. Turbulence Model

Vortices form in regions with high velocity gradients due to shear layer instabilities. In these regions, turbulent fluctuations play a critical role in momentum transport. To account for turbulence effects on the mean flow and to predict turbulent kinetic energy and dissipation rate, an appropriate turbulence model is required.

For the purpose of future two-phase analysis, a turbulence model with robust near-wall performance was required. The $k-\omega$ SST (Shear Stress Transport) model was therefore selected. This hybrid RANS model employs the $k-\omega$ formulation near the wall and the $k-\varepsilon$ formulation in the free stream, with a blending function in between[9].

2.2. Simulation Conditions

Single-phase simulations of a single fin were conducted to investigate the flow characteristics inside the fin, with water as the working fluid. As shown in Fig. 2, the computational domain consists of a fluid region, which measures $6 \times 10 \times 10.5 \text{ mm}^3$ within an overall domain of $6 \times 19 \times 13.5 \text{ mm}^3$.

The main simulation parameters are summarized in Table 2. Five cases were analyzed: one without a side slot and four with side slot widths of 1, 1.5, 2, and 3 mm. Previous studies have shown that side slots significantly modify the internal flow characteristics of the cooling channel, independent of mesh resolution ($\Delta x = 0.25 \text{ mm}$ and 0.5 mm)[8]. For a grid size of 0.5 mm , the y^+ value was 33.39, which lies in the physically acceptable range ($30 < y^+ < 300$). At this resolution, the hydrodynamic features were well resolved with manageable computational cost; thus, a mesh size of 0.5 mm was adopted for this study.

Table 2. Computational setup and key parameters

Initial Condition		
Inlet velocity	3.3	[m/s]
Temperature	323.15	[K]
Pressure	0.1	[MPa]
Numerical Model		
Turbulence model	$k-\omega$ SST	
Solver	multiphaseEuler	
Mesh		
Size	0.5	[mm]
Type	hexagonal	

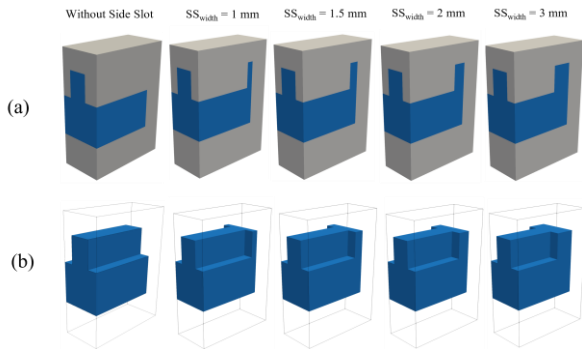


Fig. 2. Schematic of the computational domain :
(a) entire geometry and (b) fluid region

3. Results

Fig.3. shows the velocity fields for each simulation case. In the top view (Fig. 3a), the case without a side slot exhibits a predominantly unidirectional flow. In contrast, the presence of side slots induces higher velocities toward the slot, resulting in velocity vectors oriented in directions different from the relatively uniform flow of the case without a side slot. The front view (Fig. 3b) further illustrates that, in the absence of a side slot, the flow rotates uniformly within the fin. With increasing side slot width, the rotation axis of the fluid tilts along the z -direction, reducing the apparent uniform rotation in the x - y plane. Note that only the x - y plane components are displayed, as the flow progresses in the z -direction.

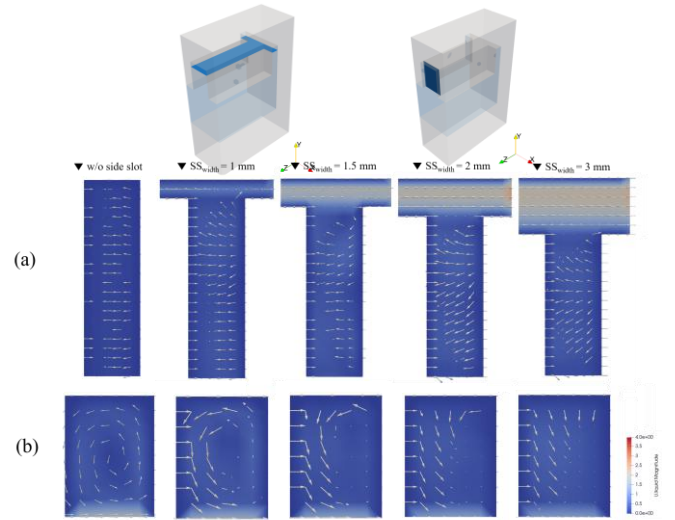


Fig. 3. Velocity fields inside the fin:
(a) top view and (b) front view

The vortex cores, representing the central axes around which the fluid rotates due to vortical motion, are depicted in Fig. 4, corresponding to the same view as in Fig. 3. As the side slot width decreases, a relatively straight vortex core develops, whereas increasing the side slot width results in a more curved and distorted core. The curvature of the vortex core arises from the vortex generation mechanism: larger velocity gradients produce stronger vortices, and as the side slot widens, the flow within the slot becomes more developed. This increases the velocity difference between the slot and the fin channel, generating a stronger vortex near the side slot. In the 3 mm case, this slot-induced vortex disrupts the otherwise uniform vortex within the fin. Consequently, the vortex core no longer follows a straight path; instead, its starting and ending points are located near the corners, reflecting a vertical deviation of the rotational axes, consistent with the observations in the front view (Fig. 4b).

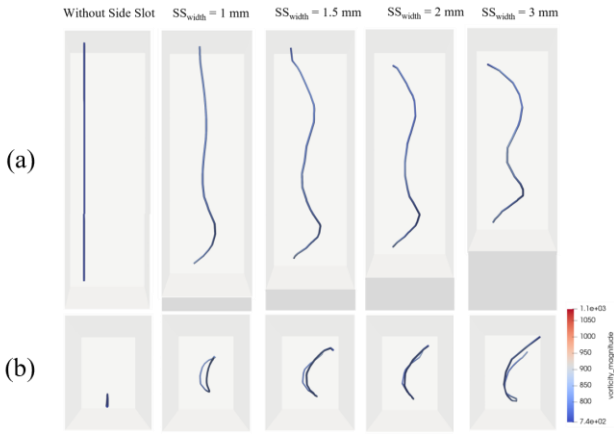


Fig. 4. Vortex core inside the fin: (a) top view and (b) front view

This phenomenon can be further interpreted using the Multiple Vortex Interaction Model (MVIM). First, the Stream–Vorticity Interaction (SVI) describes the effect of background shear flow on a vortex trajectory. When a strong velocity gradient forms between the slot and the fin channel, the originally straight vortex core within the fin begins to curve. As the side slot width increases further, Vorticity–Vorticity Interaction (VVI) becomes dominant. The strong vortex generated within the side slot interacts with the internal vortex of the fin, leading to asymmetric distortion of the vortex core through merging, deformation, and energy exchange[10].

The swirling strength, λ_{ci} , is a widely used kinematic quantity for identifying and quantifying the strength of vortical structures. It is defined as the magnitude of the imaginary part of the complex conjugate eigenvalues of the velocity gradient tensor. In contrast to vorticity, which incorporates both shear and rotational motion, λ_{ci} isolates the local rotational intensity of fluid particles, providing a more robust criterion for vortex core identification[11]. As illustrated in Fig. 5, the 1.5 mm case exhibits the highest velocity within the fin, which directly corresponds to a similar trend in the swirling strength. This correlation suggests that the increased bulk flow velocity within the narrow fin passage enhances the local rotational motion of the fluid, thereby generating a stronger swirling flow.

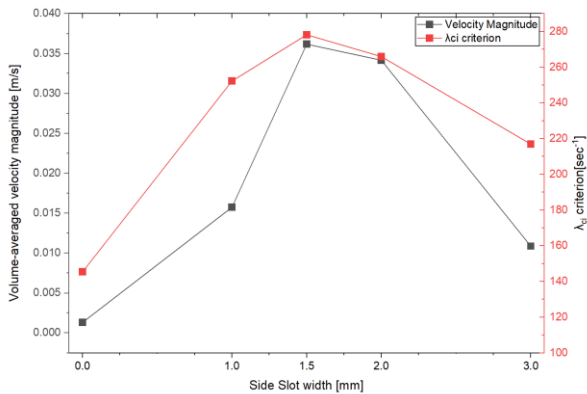


Fig. 5. Velocity magnitude(black) and swirling strength(red) as a function of side slot width

4. Conclusion

This study presents a parametric analysis of the side slot width in hypervapotron structures to optimize geometric design for efficient heat removal under high heat flux conditions. Single-phase simulations were conducted to examine vortex dynamics and their role in vapor ejection. The results indicate that narrower side slots generate more coherent vortices, whereas wider slots produce shorter and more distorted structures. This behavior is attributed to the formation of a shear layer as the primary flow is increasingly diverted toward the side slot region. Importantly, effective vapor ejection requires not only sufficient vortex strength but also favorable vortex orientation, since the vortical motion must promote vapor extraction from the fin interior rather than entrapment. These findings indicate the necessity of diabatic flow simulations incorporating heated walls to enable a comprehensive assessment of cooling performance. Furthermore, accurately capturing bubble coalescence and breakup during flow boiling requires consideration of the effects of multiple fins. Such simulations will be conducted in future work.

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