

# A Review of Heat Transfer Characteristics in Submerged Combustion Vaporizers: Advances in Icing, Fouling, and Optimization

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## Abstract

The submerged combustion vaporizer (SCV), as a critical equipment in the regasification process of liquefied natural gas (LNG), is widely used in LNG receiving terminals worldwide due to its significant advantages such as fast start-up, independence from ambient temperature, compact structure, and flexible load adjustment. This paper systematically reviews the research progress on the heat transfer characteristics of SCVs, with an in-depth analysis focusing on three core themes: icing behavior, fouling formation mechanisms and mitigation measures, as well as structural and operational optimization. Studies indicate that icing and fouling on the external surfaces of heat transfer tubes severely constrain the thermal efficiency of SCVs. Optimizing operational parameters and improving heat exchange surface structures and properties can effectively alleviate these issues.

## Keywords

SCV; LNG; Heat Transfer Characteristics; Icing; Fouling.

## 1. Introduction

Liquefied natural gas (LNG) has become an important component of the global energy structure due to its advantages of being clean, efficient, and having a small storage volume. In the LNG supply chain, vaporizers are critical equipment for converting liquid LNG into gaseous natural gas. Common types of vaporizers include submerged combustion vaporizers (SCVs), open rack vaporizers (ORVs), intermediate fluid vaporizers (IFVs), and ambient air vaporizers (AAVs). Among these, SCVs are widely used, especially in peak-shaving stations and cold regions, owing to their rapid response, strong environmental adaptability, and small footprint [1-3].

SCVs generate high-temperature flue gas by burning natural gas, which is then introduced into a water bath through bubble tubes to exchange heat with LNG flowing inside serpentine tubes, thereby vaporizing and heating it to the required outlet temperature. However, the extremely low temperature of LNG (approximately  $-162^{\circ}\text{C}$ ) can cause local icing in the surrounding water bath, increasing thermal resistance. Simultaneously, the alkaline environment and impurity ions in the water bath promote the deposition of fouling, such as calcium carbonate, on the tube walls, further reducing heat transfer efficiency [4-6]. The issues of icing and fouling not only increase natural gas consumption and operational costs but also exacerbate equipment corrosion and carbon emissions.

Although numerous studies have separately investigated the effects of icing or fouling on heat exchanger performance, systematic research on the coupled effects of both on the heat transfer mechanisms in SCVs remains limited. This paper aims to review the research progress on icing and fouling issues in SCVs, with a focus on the impact of fouling thickness and distribution on ice layer growth and heat transfer performance, to provide theoretical references for the optimal design and energy-efficient operation of SCVs.

## 2. Research Progress on Icing in SCVs

### 2.1. Icing Mechanisms and Their Effects

During SCV operation, the flow of low-temperature LNG through heat exchange tubes causes the surrounding water bath temperature to drop locally below the freezing point, resulting in the formation of an ice layer on the external tube walls. This phenomenon not only increases thermal resistance but may also cause flow channel blockages, severely affecting vaporization efficiency. Han et al. [4] conducted an in-depth study on the fluid flow and heat transfer characteristics in SCV heat exchange tubes using a visual experimental system. Their experimental results showed that the heat carried by flue gas is often insufficient to meet the heating demands of the ultra-low-temperature fluid inside the tube bundle, causing a sharp drop in the local water bath temperature below the freezing point. The study confirmed that ice layers are primarily concentrated at the bottom of the tube bundle and near the inlet liquid header. Additionally, the disturbance generated by the mixture of flue gas and water sweeping across the tube bundle has a certain ice-breaking effect. The study also indicated that the main thermal resistance in SCVs is located inside the tube bundle, providing important direction for subsequent optimization designs.

Bai et al. [5] used numerical methods to investigate the ice formation process and thermal performance characteristics in serpentine tubes, systematically analyzing the effects of operational pressure and heat flux density on heat transfer and ice layer formation. The study revealed three key phenomena: First, centrifugal forces dominate the heat transfer process in curved regions due to enhanced transverse and rotational flows. Second, compared to straight sections, curved regions cause fluid flow acceleration and secondary Reflux phenomena, significantly enhancing heat and mass transfer but also promoting ice layer formation. Finally, pressure changes affect heat transfer performance and icing by altering the thermophysical properties of the fluid, while heat flux density changes directly influence fluid temperature distribution, thereby impacting ice formation and heat transfer processes.

### 2.2. Anti-Icing Measures and Optimization Strategies

To address icing issues in SCVs, researchers have conducted in-depth studies from two perspectives: operational parameter optimization and surface property improvements. Pan et al. [6,7] developed a theoretical model of SCV icing behavior based on energy balance equations, systematically studying the influence of operational parameters on icing characteristics. The results showed that due to the low temperature of LNG, the lower external surface of the tubes is most prone to ice formation. As the tube length increases, the temperatures of LNG and the tube wall gradually rise, leading to a gradual reduction in ice layer thickness. When operational pressure increases, ice layer length slightly decreases, while average ice thickness continues to decline. With increasing operational load, average ice thickness decreases, whereas ice layer length first increases and then rapidly decreases. Additionally, as the inlet LNG temperature rises, the required minimum water bath temperature and flue gas flow rate decrease, but ice layer length changes relatively little. These findings provide important guidance for SCV operational optimization.

Qi et al. [8] established a one-dimensional heat transfer model for SCVs, based on assumptions such as stable LNG flow, negligible environmental heat leakage, and pressure drop. They used a modified Jackson formula to calculate the forced convection heat transfer coefficient inside the tubes and applied formulas proposed by Churchill and Bernstein to calculate the external heat transfer coefficient. By systematically analyzing the effects of water bath temperature and internal LNG temperature on icing, the study found that icing on SCV heat exchange tube surfaces leads to deteriorated heat transfer performance and reduced operational capacity.

Increasing the water bath temperature and the temperature of the heat transfer medium inside the tubes can effectively inhibit ice formation.

In surface engineering applications, He et al. [9] experimentally studied the effects of different surface properties (hydrophobic, hydrophilic, and superhydrophobic) on the icing performance of heat exchangers. The study analyzed crystal growth patterns, ice layer formation, and blockages during the icing process and compared their de-icing performance. The results demonstrated that superhydrophobic surfaces perform best in inhibiting ice formation and minimizing reductions in heat exchange efficiency, providing new insights for addressing icing issues through surface modification technologies.

### 3. Current Status of Fouling in SCVs

#### 3.1. Fouling Formation Mechanisms and Characteristics

Common fouling components in SCV water baths include insoluble salts such as calcium carbonate ( $\text{CaCO}_3$ ) and calcium sulfate ( $\text{CaSO}_4$ ). The deposition process of these substances on heat transfer surfaces is influenced by various factors, including temperature, flow velocity, water quality composition, and surface properties. Berce et al. [10] comprehensively reviewed crystallization fouling in heat exchangers, that temperature increases typically reduce salt solubility, thereby increasing solution supersaturation and promoting fouling formation. The study also found that rough surfaces facilitate fouling attachment and accumulation compared to smooth surfaces, and all inverse solubility salt solutions exhibit increased deposition rates with higher heat exchanger inlet temperatures.

Han et al. [11] numerically simulated the local deposition characteristics of calcium carbonate in different enhanced tubes, systematically comparing the fouling inhibition effects of four tube types. The results showed that corrugated tubes have the best anti-fouling performance, being 1.27 times more effective than smooth tubes. The order of fouling inhibition effectiveness from best to worst was: corrugated tubes, arc-shaped tubes, and converging-diverging tubes.

#### 3.2. Anti-Fouling Technologies and Control Strategies

In anti-fouling technology research, Hasan et al. [12] experimentally studied the effects of common dissolved salts on tube fouling, using sodium sulfate solutions and cold water as research subjects. They analyzed the influence of temperature parameters on crystallization fouling formation and growth. The results indicated that factors reducing surface temperature promote fouling, while those increasing surface temperature inhibit fouling formation.

Albert et al. [13] conducted crystallization fouling experiments with calcium sulfate solutions in a double-pipe heat exchanger. Using three detection methods (fluid dynamic analysis based on pressure drop measurements, heat transfer performance testing, and endoscopic optical inspection), they studied the fouling process. The study found that crystal formation and fouling accumulation produce two main effects: increased surface roughness and flow channel constriction due to fouling development, both of which jointly affect the hydrodynamic and thermal performance of heat exchangers. Interestingly, in the early stages of fouling, the presence of fouling increases surface roughness, enhancing turbulence at the fluid-heat exchange interface and thus improving heat transfer.

Lv et al. [14] investigated the impact of salt deposition in solutions on heat transfer performance through coupled studies of fouling and heat transfer. Experimentally studying the fouling process of mixed salt solutions with different mass ratios under varying temperatures and flow velocities, they precisely measured changes in heat transfer coefficients and thermal resistance. The results showed that as the fouling layer grows, the heat transfer coefficient gradually decreases, while thermal resistance increases, quantitatively describing the negative impact of fouling on heat transfer performance.

## 4. Research Progress on SCV Heat Transfer Optimization

### 4.1. Structural Optimization and Enhanced Heat Transfer Technologies

In SCV optimization studies, structural improvements are an important way for enhancing thermal performance. Park et al. [15] conducted systematic numerical calculations on SCVs, showing that adding fins to the external surfaces of heat exchange tube bundles significantly increases the heat transfer area, leading to higher heat transfer efficiency. The study emphasized the need to balance two competing processes: enhanced heat transfer and increased pressure drop. As the Reynolds number increases, the heat transfer coefficient rises, but pressure drop also increases due to higher flow velocities, necessitating an optimal balance.

Pan et al. [6,7] studied enhanced heat transfer in SCV tube bundles, analyzing the effects of 45° twisted tapes, and 45° and 75° helical coil inserts on SCV heat exchange performance. The study found that under both supercritical and subcritical pressures, all three inserts significantly enhanced heat transfer, with 75° helical coils showing the most pronounced effect.

Bai et al. [16] established a three-dimensional numerical model to study the effects of artificial roughness on LNG heat transfer characteristics in SCVs under supercritical conditions. The results showed that under the same heating conditions, the outlet temperature of natural gas in artificially roughened tubes was 17.63% higher than in smooth tubes, indicating significant heat transfer enhancement. However, the study also noted that in curved regions, enhanced heat transfer due to artificial roughness transfers more LNG cold energy to the tube walls, promoting ice formation. Thus, applying artificial roughness only in straight tube sections is a beneficial strategy for improving overall system thermal performance and inhibiting ice formation.

### 4.2. Operational Parameter Optimization and Performance Enhancement

Operational parameters directly affect SCV performance, and related studies provide theoretical guidance for optimization. Song et al. [17] studied the effect of initial liquid level height on the external heat transfer coefficient of tube bundles. The results showed that at lower initial liquid levels, two-phase flow velocity and volumetric gas fraction are relatively high, and the external heat transfer coefficient is primarily influenced by gas fraction. As the initial liquid level increases, gas fraction decreases, enhancing heat transfer. At higher initial liquid levels, two-phase flow velocity and gas fraction are smaller, and the external heat transfer coefficient is mainly affected by two-phase flow velocity. Increasing the initial liquid level reduces two-phase flow velocity, leading to deteriorated heat transfer.

Yu et al. [18] conducted detailed heat transfer studies on the gas fraction in SCV water baths and the opening of flue gas tubes. The study found that increased gas fraction at high relative loads inhibits heat transfer, shifting the thermophysical properties of the gas-liquid two-phase flow toward the gaseous phase and causing deviations between actual and required external heat transfer coefficients. The opening of flue gas tubes affects the agitation of the water bath by flue gas and the overall external heat transfer. Higher openings avoid high gas fraction phenomena caused by local strong agitation, improving the external heat transfer coefficient under different loads and alleviating insufficient heat transfer coefficients at high loads.

## 5. Summary

Through a systematic literature review, it is evident that research on SCV heat transfer characteristics has yielded rich results in icing mechanisms, fouling characteristics, and optimization measures. In icing research, experimental and numerical studies have revealed ice formation mechanisms and influencing factors, showing that operational parameter optimization and surface modifications can effectively mitigate icing issues. In fouling research,

studies have identified key factors influencing fouling formation and explored the anti-fouling performance of different tube structures and surface properties, providing a basis for selecting optimal materials and treatment processes. In optimization research, various methods for enhancing heat transfer through structural improvements and operational parameter adjustments have been proposed.

However, current research still has notable limitations. First, most studies analyze icing or fouling in isolation, lacking dynamic modeling and experimental validation of heat transfer characteristics under coupled ice-fouling interactions, making it difficult to reflect actual operational complexities. Second, the non-uniformity of fouling distribution, positional effects, and their relationship with flow structures have not been thoroughly explored, limiting accurate prediction and control of fouling processes. Third, existing structural optimization and operational control studies often focus on single-objective optimization, lacking multi-parameter collaborative optimization and system-level performance evaluation, making it challenging to achieve overall optimal performance.

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