# Impact of Quench-Mixing Devices on Hydrogen Utilization in Multi-Bed Trickle-Bed Hydroprocessing Reactors: Design, Performance, and Industrial Implications

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**Abstract**

Efficient quench-mixing devices play a pivotal role in multi-bed trickle-bed hydroprocessing reactors, ensuring uniform temperature distribution, enhanced phase mixing, and optimal hydrogen utilization. Hydroprocessing reactions are highly exothermic, and localized hotspots can accelerate catalyst deactivation, reduce selectivity, and increase hydrogen consumption. Inter-stage quench systems, through momentum-driven mixing, turbulent eddy diffusion, and interfacial mass transfer, mitigate these challenges by promoting uniform hydrogen distribution and thermal control. This review presents a comprehensive examination of quench-mixing device fundamentals, classifications, industrial designs, computational modelling approaches, and future trends. Particular emphasis is placed on the impact of quench device performance on hydrogen efficiency, demonstrating that optimized designs not only enhance thermal management but also reduce operational hydrogen requirements, lowering refinery costs and improving sustainability. Historical developments, patented systems, and modern multi-zone and compact designs are discussed to highlight best practices and future directions for advancing hydrogen utilization in hydroprocessing reactors.

## 1. Introduction and Background

Trickle-bed reactors (TBRs) are widely employed in hydroprocessing operations within petroleum refineries, including hydrodesulfurization (HDS), hydrodenitrogenation (HDN), hydrodemetallation, and hydrocracking. These reactors consist of packed catalyst beds through which liquid hydrocarbons flow downward, counterbalanced by co-current or counter-current hydrogen gas. This gas–liquid–solid contact is critical for achieving high conversion rates and selectivity while maintaining catalyst activity over extended operational periods.

Hydroprocessing reactions are typically highly exothermic, producing significant heat fluxes that can exceed several megawatts per cubic meter of catalyst. Without effective inter-stage temperature control, localized hotspots may form, leading to several undesirable effects: accelerated catalyst deactivation, reduced hydrogen partial pressure, lower selectivity, increased coking, and fouling. These issues not only impact product quality but also elevate operational costs, particularly due to increased hydrogen consumption and reduced reactor lifetime.

To address these challenges, inter-stage quench systems are introduced between catalyst beds. These systems typically inject a cooled hydrogen-rich stream into the reactor, achieving three main objectives: (1) controlling the temperature rise within the bed to prevent hotspots, (2) enhancing radial and axial distribution of gas and liquid phases, and (3) maintaining sufficient hydrogen availability throughout the reactor volume. Effective quench-mixing is therefore not only a thermal management strategy but also a key contributor to hydrogen utilization efficiency, which has direct economic implications in refinery operations. Poorly mixed quench streams can create zones with limited hydrogen availability, forcing operators to increase total hydrogen supply to maintain reaction kinetics, thereby raising operating costs. Conversely, well-engineered quench systems promote uniform hydrogen distribution, reduce bypassing, and enable the same conversion with lower hydrogen flow rates.

Quench devices in modern TBRs must meet multiple design criteria: rapid thermal equilibration, uniform radial and axial distribution of gas and liquid phases, minimal pressure drop to conserve compressor energy, resistance to fouling and scaling, and scalability to industrial diameters exceeding 3–5 meters. Common configurations include quench injection nozzles or ring injectors, flow-conditioning baffles, swirl chambers, and downstream distribution trays. Their design must account for hydrodynamic phenomena, gas–liquid mass transfer, residence time distributions, and the interactions between injected quench streams and existing trickling phases.

Over the past five decades, quench-mixing devices have evolved considerably. Early designs focused primarily on promoting turbulence for temperature control, while modern innovations incorporate multi-zone architectures, optimized gas–liquid interfaces, and fouling-resistant internals to enhance both thermal uniformity and hydrogen utilization. The evolution of these devices reflects the dual need to ensure high reaction efficiency while minimizing hydrogen consumption, highlighting the intrinsic link between quench performance, reactor safety, and economic optimization in hydroprocessing operations.

In this review, we provide a comprehensive examination of quench-mixing devices, focusing on hydrodynamic principles, mixing mechanisms, historical development, industrial applications, computational modeling, and emerging trends. The review emphasizes the impact of quench design on hydrogen utilization, positioning efficient mixing as a critical lever for improving refinery efficiency and lowering operational costs.

# 2. Fundamentals of Quench-Mixing

Efficient quench-mixing in multi-bed trickle-bed reactors is governed by a combination of fluid mechanics, multiphase hydrodynamics, and mass transfer phenomena. The primary goal of a quench device is to rapidly and uniformly distribute both heat and hydrogen across the catalyst bed, thereby mitigating hotspots and ensuring consistent reaction conditions. Achieving this requires an understanding of the fundamental hydrodynamic and mass transfer mechanisms that control gas–liquid interactions within the reactor.

## 2.1 Hydrodynamic Principles

The flow behaviour of gas and liquid phases in a packed bed is highly complex, characterized by simultaneous trickling of liquid over catalyst particles and the upward or co-current passage of hydrogen gas. Quench-mixing introduces additional streams of liquid and hydrogen, which interact with the existing flow to produce turbulence and enhance radial and axial homogenization.

Dimensionless numbers provide critical insight into the flow regimes and mixing characteristics:

- Reynolds number (Re) defines whether the liquid phase is in laminar or turbulent flow. In large-diameter reactors, Reynolds numbers are typically in the transitional to turbulent regime, facilitating effective momentum-driven mixing.
- Froude number (Fr) compares inertial forces to gravitational forces, particularly relevant for downward trickle flow, jet impingement, and liquid spreading over catalyst particles.
- Weber number (We) governs droplet breakup and atomization when high-velocity jets impinge on the liquid phase. Proper atomization enhances the gas–liquid interfacial area, critical for hydrogen mass transfer.

Through the careful design of injection nozzles, swirl chambers, and baffles, quench devices manipulate these hydrodynamic forces to generate controlled turbulence. Turbulence, in turn, reduces radial and axial temperature gradients, improves reactant distribution, and minimizes localized hydrogen starvation zones, thereby enhancing overall hydrogen utilization.

## 2.2 Mechanisms of Mixing

Quench-mixing operates through three interconnected mechanisms:

1. **Momentum-driven mixing** occurs when injected liquid or gas jets collide or swirl within the quench zone. The kinetic energy of the streams generates macroscopic turbulence, rapidly redistributing both heat and fluid momentum. The resulting eddies facilitate homogenization across the reactor cross-section and reduce the likelihood of hotspots forming near the reactor wall or catalyst surfaces. Momentum-driven mixing is particularly effective in multi-zone devices, where subsurface injection ensures that thermal energy and reactants are uniformly distributed before entering the next catalyst bed.
2. **Turbulent eddy diffusion** acts at smaller scales, breaking the fluid into micro-scale vortices that enhance local gas–liquid contact. These eddies promote fine-scale mixing, increasing the surface area available for hydrogen dissolution and facilitating uniform concentration distribution within the liquid phase. In high-diameter reactors, where radial maldistribution of liquid or gas can occur, turbulent eddies are essential for maintaining homogeneous conditions and preventing localized hydrogen deficiency, which could otherwise reduce reaction rates and force increased hydrogen supply.
3. **Interfacial mass transfer** governs the dissolution of hydrogen into the hydrocarbon liquid. The rate of hydrogen absorption depends on the interfacial area, turbulence intensity, bubble or droplet size, and local flow conditions. Atomization, bubble breakup, and high-shear jet impingement all contribute to enhanced gas–liquid contact, increasing the local mass transfer coefficient ($k_La$). Efficient interfacial mass transfer ensures that sufficient hydrogen is available for kinetically demanding reactions, reduces unreacted hydrogen venting, and improves overall refinery efficiency.

## 2.3 Residence Time and Flow Distribution

Residence time distribution (RTD) within the quench zone is a critical determinant of mixing efficiency. Insufficient residence time can result in short-circuiting or bypassing, where portions of the liquid or gas traverse the bed with minimal contact, creating regions of hydrogen deficiency and thermal non-uniformity. Conversely, excessive residence time or overly aggressive mixing can increase pressure drop, induce liquid fallback, and reduce operational efficiency. Optimal quench design balances these factors, ensuring adequate residence for thorough mixing without penalizing pressure drop or hydrogen consumption.

## 2.4 Implications for Hydrogen Utilization

Hydrogen utilization in multi-bed TBRs is intrinsically linked to quench-mixing performance. Poor mixing can create regions of local hydrogen starvation, reducing the effectiveness of hydroprocessing reactions and forcing operators to increase overall hydrogen feed. Effective quench-mixing ensures that hydrogen is evenly distributed, minimizing bypass, maximizing dissolution into the liquid phase, and maintaining consistent reaction kinetics. In practical terms, improved hydrogen utilization reduces the load on compressors, decreases operational costs, and contributes to more sustainable refinery operations.

Furthermore, modern quench devices that integrate **multi-zone injection, swirl chambers, and subsurface distribution** not only provide superior thermal control but also optimize hydrogen availability. These devices prevent the formation of dead zones, enhance radial uniformity, and reduce the total hydrogen required for a given reaction load, demonstrating the dual role of quench devices in thermal management and resource efficiency.

# 3. Classification and Performance of Quench Devices

Quench-mixing devices in trickle-bed hydroprocessing reactors serve a dual purpose: controlling the temperature rise between catalyst beds and ensuring uniform distribution of hydrogen and liquid hydrocarbons. Over the decades, device design has evolved to address hydrodynamic, thermal, and mass transfer challenges, with innovations aimed at reducing pressure drop, minimizing fouling, and improving hydrogen utilization efficiency. Quench devices can be broadly classified into **vortex mixers, baffled-box mixers, impingement devices, annular collision mixers, segregated-phase mixers, hybrid devices, and advanced multi-zone or**

**compact designs**. Each class exhibits distinct operational principles, advantages, and limitations, which influence their selection for industrial applications.

## 3.1 Vortex Mixers

Vortex mixers represent one of the earliest approaches to inter-stage quenching. These devices employ tangential or axial injection to impart rotational flow within the quench zone. The swirling motion generates macro-scale turbulence that promotes radial and axial mixing.

**Advantages:**

- Compact and simple design, allowing retrofitting into existing reactors.
- Moderate turbulence is sufficient to reduce major temperature gradients.

**Limitations:**

- Micro-scale gas–liquid contact remains limited, reducing hydrogen dissolution efficiency in larger reactors.
- Risk of liquid fallback or maldistribution, particularly at high turndown ratios.

**Industrial relevance:** Vortex mixers were widely adopted in early hydroprocessing units with moderate flow rates. They provide reasonable thermal control but are less effective for hydrogen utilization optimization in large-diameter reactors.

## 3.2 Baffled-Box Mixers

Baffled-box mixers employ a series of expansions, contractions, and baffles to generate turbulence and redirect the flow across the reactor cross-section. This configuration enhances both radial and axial mixing and improves phase homogenization.

**Advantages:**

- Strong macro-scale mixing, reducing radial temperature differences and promoting uniform hydrogen distribution.
- Effective for large-diameter reactors where temperature control is critical.

**Limitations:**

- Higher pressure drop (typically 0.1–0.2 bar), which increases hydrogen compression energy requirements.
- Presence of stagnant zones may lead to fouling or coking over prolonged operation.

**Industrial relevance:** Baffled-box designs remain relevant in applications where $\Delta T$ control is more critical than pressure drop minimization. They demonstrate moderate improvement in hydrogen utilization but require careful maintenance to prevent fouling.

## 3.3 Impingement Devices

Impingement devices operate by colliding liquid jets on flat plates or surfaces within the quench chamber, converting kinetic energy into turbulence and enhancing mixing.

**Advantages:**

- Simple fabrication and moderate turbulence generation.
- Effective in small-to-medium diameter reactors.

**Limitations:**

- Limited gas–liquid interfacial area for hydrogen dissolution.
- Surface scaling may reduce efficiency over time.

**Industrial relevance:** Impingement devices offer straightforward solutions for targeted temperature control but are less suitable when hydrogen utilization optimization is a priority.

## 3.4 Annular Collision Mixers

Annular collision mixers direct opposing liquid jets to collide within annular rings, generating momentum-driven turbulence.

**Advantages:**

- Provides compact footprint with controlled radial and axial mixing.
- Jet collision enhances local turbulence intensity.

**Limitations:**

- Sensitive to flow variation; deviations in liquid or gas flow rates can reduce performance.
- Moderate scalability for very large-diameter reactors.

**Industrial relevance:** Annular collision mixers have been used in specialty hydroprocessing applications where compact, high-intensity mixing is needed. Hydrogen distribution is improved in the immediate quench zone but requires precise flow control.

## 3.5 Segregated-Phase Mixers

Segregated-phase mixers pre-mix gas and liquid separately and then recombine them downstream. This design allows controlled wetting of catalyst particles and uniform distribution at low gas velocities.

**Advantages:**

- Enables controlled hydrogen-liquid interaction, reducing bypassing.
- Effective in low-gas-flow conditions, improving hydrogen utilization.

**Limitations:**

- Complex geometry and internal channels.
- Limited scalability for very large reactors due to pressure drop concerns.

**Industrial relevance:** Segregated-phase mixers are applied in reactors where maintaining precise gas–liquid ratios is critical for reaction kinetics and hydrogen efficiency.

## 3.6 Vortex–Bubble Cap Hybrids

Hybrid designs combine the rotational flow of vortex mixers with bubble caps or vapor-lifting features to enhance gas–liquid contact.

**Advantages:**

- Improved hydrogen dissolution due to enhanced interfacial area and vapor lift preventing gas channeling.
- More uniform liquid distribution across the bed.

**Limitations:**

- Higher pressure drop compared to simple vortex or annular devices.
- Complex fabrication and maintenance requirements.

**Industrial relevance:** These hybrid designs provide a balance between turbulence generation and hydrogen availability, particularly in moderate-to-large diameter reactors.

### 3.7 Advanced Compact and Multi-Zone Devices

Modern hydroprocessing units increasingly employ **compact, multi-zone, or modular designs**, incorporating swirl chambers, subsurface injection, and specialized baffle arrangements. Key examples include:

- **UOP Compact Quench Zone (US 10,486,127 B2; US 11,298,670 B2):** Shallow swirl chambers reduce height while maintaining radial uniformity. Effective for hydrogen distribution with minimal pressure drop.
- **Shell Ultra-Flat Quench (UFQ):** Vertical liquid jets with gas swirl vanes; radial ΔT typically 1–4°C; fouling-resistant and compact (<1 m height).
- **Chevron Multi-Zone Distributor:** Arc-shaped baffles, subsurface quench injection, and doughnut-shaped screens; radial ΔT 1–3°C; low pressure drop (<0.06 bar); enhances hydrogen distribution across wide turndown ratios.

These advanced devices demonstrate the **synergistic effect of improved mixing and hydrogen utilization**, highlighting the importance of modern quench design in operational efficiency and cost reduction.

### 3.8 Comparative Insights and Hydrogen Utilization Implications

Across the range of devices, several trends emerge:

1. **Turbulence intensity correlates with hydrogen dissolution:** Devices that generate higher turbulence at both macro and micro scales improve local hydrogen availability and minimize bypass.
2. **Pressure drop vs. mixing trade-off:** Devices with stronger mixing often impose higher pressure drop. Modern designs mitigate this by using multi-zone architectures and swirl chambers.
3. **Scalability and fouling resistance:** Advanced compact designs allow large-diameter reactors to achieve uniform phase distribution while reducing maintenance requirements.
4. **Hydrogen efficiency:** Effective quench-mixing reduces local hydrogen starvation, enabling the same conversion with lower total hydrogen flow, thus reducing operational costs.

## 4. Detailed Working Principles of Quench-Mixing Devices

Understanding the working principles of quench-mixing devices is essential for designing systems that achieve uniform temperature and hydrogen distribution while minimizing pressure drop and operational inefficiencies. Modern quench devices employ a combination of **momentum-driven mixing, turbulent eddy diffusion, interfacial mass transfer, and multi-zone integration**, each contributing to enhanced thermal management and hydrogen utilization.

### 4.1 Momentum-Driven Mixing

Momentum-driven mixing arises when injected liquid and gas streams impart kinetic energy into the quench zone. Devices such as vortex mixers, annular collision mixers, and impingement plates rely on **jet impingement, swirl generation, and flow redirection** to convert momentum into turbulent energy.

- **Jet dynamics:** Liquid jets typically enter the quench zone with velocities ranging from 2–5 m/s. Upon collision with other jets or impact surfaces, the kinetic energy is rapidly redistributed, generating macro-scale turbulence.

- **Swirl chambers and rotational flow:** Tangential injection induces a vortex motion that spreads liquid radially and distributes gas uniformly, mitigating the risk of bypass channels.
- **Impact on hydrogen utilization:** Momentum-driven mixing ensures that fresh hydrogen is entrained into the liquid phase, reducing local starvation and promoting uniform reaction kinetics across the catalyst bed.

The design of momentum-driven systems must carefully balance jet velocity, nozzle geometry, and injection angle to prevent excessive pressure drop or liquid fallback, which can compromise both energy efficiency and hydrogen availability.

## 4.2 Turbulent Eddy Diffusion

While momentum-driven mixing addresses macro-scale fluid redistribution, **turbulent eddy diffusion** operates at smaller scales to enhance local mixing and interfacial contact.

- **Eddy formation:** Shear layers between high-velocity jets and quiescent fluid produce vortices of varying sizes. Micro-scale eddies promote fine-scale mixing, increasing the interaction between liquid hydrocarbons and hydrogen gas.
- **Radial and axial homogenization:** Turbulent eddies minimize temperature gradients and solute concentration differences across the reactor cross-section. In large-diameter reactors, this mechanism is particularly important to prevent localized hydrogen depletion zones.
- **Residence time implications:** Proper design ensures that the eddy diffusion length and timescale are sufficient for thorough mixing without introducing excessive pressure drop or liquid fallback.

Turbulent eddy diffusion thus complements momentum-driven mechanisms by promoting **micro-scale gas–liquid contact**, which directly affects hydrogen dissolution and utilization.

## 4.3 Interfacial Mass Transfer

Interfacial mass transfer governs the absorption of hydrogen into the liquid hydrocarbons, a key factor influencing hydroprocessing kinetics and hydrogen efficiency. The **rate of hydrogen dissolution** depends on the interfacial area, turbulence intensity, and contact time.

- **Gas–liquid interfaces:** Atomization, jet impingement, and bubble dispersion increase the surface area for hydrogen transfer. Devices such as vortex–bubble cap hybrids and segregated-phase mixers are designed to maximize this effect.
- **Mass transfer coefficient ($k_La$):** The local $k_La$ is a function of turbulence, droplet size, bubble residence time, and liquid velocity. Higher $k_La$ values correlate with improved hydrogen availability and reduced overall hydrogen feed requirements.
- **Industrial impact:** Efficient interfacial mass transfer ensures that hydrogen consumption is minimized without compromising reaction rates, directly translating to operational cost savings. Poorly designed quench zones, in contrast, create hydrogen-deficient pockets that force increased hydrogen supply to achieve the same conversion.

## 4.4 Multi-Zone Integration

Modern quench-mixing devices frequently employ **multi-zone architectures** to optimize both thermal and chemical performance. Multi-zone designs divide the quench region into sub-chambers, each serving a specific function in momentum redistribution, turbulence generation, and phase contact.

- **Subsurface injection:** Injecting quench streams below the liquid surface promotes thorough mixing before the fluid enters the next catalyst bed, eliminating dead zones and minimizing fallback.
- **Sequential mixing zones:** Multi-zone configurations allow stepwise equilibration of temperature and hydrogen concentration, reducing radial $\Delta T$ to as low as 1–3°C in advanced designs such as the Chevron Multi-Zone Distributor.

- **Synergy of mechanisms:** Multi-zone systems combine momentum-driven mixing, turbulent eddy diffusion, and enhanced mass transfer, providing comprehensive control over thermal gradients and hydrogen distribution.
- **Operational flexibility:** These designs support wide turndown ratios (40–130%), allowing reactors to handle variable feed rates without sacrificing mixing efficiency or hydrogen utilization.

### 4.5 Integration with Reactor Hydrodynamics

The effectiveness of quench devices depends not only on their internal design but also on their interaction with the **overall reactor hydrodynamics**. The device must accommodate:

- Downward trickling liquid flow, with potential channeling along the wall or packing voids.
- Co-current or counter-current hydrogen flow, which may be affected by gas bypass or poor wetting.
- Catalyst bed heterogeneity, including packing distribution and surface wetting efficiency.

By aligning the quench device design with reactor hydrodynamics, engineers can optimize the balance between **thermal control, phase distribution, and hydrogen utilization**, achieving both safe operation and cost-effective hydrogen management.

### 4.6 Summary of Functional Principles

In summary, the working principles of quench-mixing devices are built upon the interplay of:

1. **Momentum-driven mixing** for macro-scale turbulence and bulk fluid redistribution.
2. **Turbulent eddy diffusion** for micro-scale homogenization and radial uniformity.
3. **Interfacial mass transfer** to maximize hydrogen absorption into the liquid phase.
4. **Multi-zone integration** to sequentially equilibrate temperature and hydrogen concentration across large-diameter reactors.

This integrated approach ensures that **thermal and chemical gradients are minimized**, hydrogen utilization is optimized, and reactor performance is maintained across varying operating conditions. Modern designs leverage these principles to reduce operating costs, enhance catalyst life, and support flexible refinery operations.

## 5. Historical Evolution and Patented Systems

The development of quench-mixing devices in trickle-bed hydroprocessing reactors reflects decades of incremental innovation driven by the need for **improved thermal control, enhanced hydrogen utilization, and operational reliability**. Understanding this historical evolution provides insight into the design rationale, limitations of earlier devices, and the technological principles underlying modern systems.

### 5.1 Early Designs: Vortex and Baffled-Box Mixers (1970s–1980s)

The first commercially implemented quench devices focused on achieving **macro-scale mixing and temperature control** using relatively simple geometries.

- **Vortex Mixers:** Early vortex mixers employed tangential or axial injection to generate swirling motion within the quench zone. Their design simplicity made them attractive for retrofitting into existing reactors. However, while vortex-induced turbulence reduced some temperature gradients, the limited gas–liquid interfacial area constrained hydrogen absorption. Furthermore, at high turndown ratios, vortex mixers exhibited **liquid fallback** and maldistribution, which could reduce effective hydrogen utilization and compromise selectivity.
- **Baffled-Box Mixers:** Baffled-box designs used expansions, contractions, and strategically placed baffles to redirect flow, enhancing radial mixing and reducing hotspots. Industrially, these devices were widely adopted for **large-diameter reactors where thermal uniformity was critical**. Their main drawbacks included higher pressure drop (0.1–0.2 bar) and potential fouling in stagnant zones, which could impede hydrogen distribution. Despite these limitations, these early designs established the

fundamental principle that **momentum-driven turbulence improves both thermal control and gas–liquid interaction**.

## 5.2 UOP Swirl Chambers (2000s)

With increasing reactor diameters and tighter hydrogen efficiency requirements, compact swirl chambers were introduced by UOP in the early 2000s (US 10,486,127 B2; US 11,298,670 B2). These designs sought to **reduce quench zone height** while maintaining radial uniformity and efficient hydrogen distribution.

- **Design features:** Shallow swirl chambers with tangential injection promoted rotational flow and enhanced eddy diffusion at both macro and micro scales.
- **Industrial impact:** These devices reduced pressure drop ($\Delta P \approx 0.05$–$0.08$ bar) and radial $\Delta T$ to 2–5°C. By improving hydrogen contact with the liquid phase, swirl chambers contributed to more uniform hydrogen utilization, minimizing excess hydrogen feed.
- **Significance:** The UOP designs represented a shift from purely thermal-focused quench devices to **systems integrating both thermal control and hydrogen management**, reflecting the growing awareness of hydrogen utilization as an operational cost driver.

## 5.3 Shell Ultra-Flat Quench (UFQ) Systems (2010s)

The Shell UFQ system further refined quench-mixing design principles, targeting **compactness, fouling resistance, and wide turndown capability**.

- **Design approach:** UFQ employs vertical liquid jets coupled with gas swirl vanes, creating controlled turbulence and uniform radial distribution in reactors with diameters exceeding 5 meters.
- **Performance characteristics:** Radial $\Delta T$ is typically 1–4°C, with a pressure drop below 0.07 bar. The design also resists fouling, reducing maintenance and ensuring consistent hydrogen availability.
- **Hydrogen utilization implications:** The combination of vertical jets and swirl vanes enhances hydrogen dissolution in the liquid phase, reducing localized starvation and optimizing the hydrogen feed rate. This illustrates the growing industrial emphasis on **efficient hydrogen use as a key design metric**.

## 5.4 Chevron Multi-Zone Distributors (2015)

Chevron advanced quench-mixing technology with **multi-zone distributors** featuring arc-shaped baffles, subsurface quench injection, and doughnut-shaped screens (US 9,079,141 B2).

- **Design rationale:** Segmenting the quench zone into multiple sub-chambers ensures stepwise equilibration of temperature and hydrogen concentration. Subsurface injection prevents dead zones and liquid fallback.
- **Performance metrics:** Radial $\Delta T$ is reduced to 1–3°C, pressure drop is minimal (<0.06 bar), and wide turndown ratios (40–130%) are supported.
- **Impact on hydrogen efficiency:** By enhancing uniformity across large-diameter reactors, Chevron's design minimizes hydrogen bypass and maximizes effective utilization, allowing operators to maintain conversion with lower hydrogen flow rates.

### 5.5 IFP Energies Nouvelles and Haldor Topsoe Innovations

Specialized quench devices have been developed for niche hydroprocessing applications:

- **Ring injectors and annular mixers** by IFP Energies Nouvelles focus on controlled liquid dispersion and momentum-driven turbulence to maintain uniform catalyst wetting at low gas velocities (US 9,452,411 B2).
- **Distributor systems by Haldor Topsoe** emphasize fouling resistance and uniform phase distribution across large-diameter beds (US 7,601,310 B2).

While these systems are less widely deployed than Chevron or Shell designs, they illustrate the diversity of industrial approaches and the importance of **customizing quench devices for specific hydrogen management and thermal control requirements**.

### 5.6 Trends and Evolutionary Insights

From the early vortex and baffled-box mixers to modern multi-zone distributors, several key trends are evident:

1. **Height reduction and compact design:** Modern systems prioritize minimizing quench zone height without sacrificing mixing effectiveness, supporting reactor retrofitting and compact footprint.
2. **Multi-scale turbulence:** Devices now combine macro-scale momentum-driven mixing with micro-scale eddy diffusion to improve hydrogen dissolution and thermal uniformity.
3. **Hydrogen utilization as a design metric:** Earlier devices emphasized thermal control, but contemporary designs explicitly consider **hydrogen distribution and efficiency**, linking quench performance directly to operational cost reduction.
4. **Fouling resistance and maintenance:** Advanced devices integrate features such as swirl vanes, screens, and robust materials to reduce coking and fouling, ensuring sustained hydrogen availability and stable reactor operation.

The historical evolution of quench devices demonstrates a continuous effort to **integrate thermal management, phase distribution, and hydrogen utilization**. Patented innovations by UOP, Shell, Chevron, IFP Energies, and Haldor Topsoe highlight how improvements in design have enabled:

- Reduced pressure drop and energy consumption.
- Enhanced radial and axial uniformity of temperature and hydrogen concentration.
- Increased operational flexibility across variable feed rates.
- Optimized hydrogen utilization, reducing excess hydrogen feed and operational costs.

By understanding these historical developments, engineers can better appreciate the rationale for modern device architectures and the underlying hydrodynamic and mass transfer principles that govern their performance.

## 6. Comparative Performance and Industrial Considerations

The selection and performance evaluation of quench-mixing devices in trickle-bed hydroprocessing reactors is a multidimensional exercise, requiring careful consideration of **thermal control, pressure drop, phase distribution, fouling resistance, scalability, and hydrogen utilization efficiency**. Beyond their hydrodynamic function, quench devices directly influence reactor operation, energy consumption, and overall refinery economics.

### 6.1 Thermal and Hydrodynamic Performance

A primary metric for quench performance is the **radial and axial temperature uniformity** achieved downstream of the quench zone. Devices such as multi-zone distributors and ultra-flat quench (UFQ) systems consistently achieve radial $\Delta T$ values of 1–3°C, whereas earlier vortex mixers and impingement devices typically produce $\Delta T$ values of 5–8°C.

- **Impact on catalyst and reaction kinetics:** Lower temperature gradients prevent hotspot formation, which reduces localized catalyst deactivation, coking, and undesired side reactions.
- **Link to hydrogen utilization:** Uniform temperature distribution ensures that hydrogen solubility and reaction kinetics remain consistent across the bed. Poor thermal control can create regions of hydrogen starvation, forcing higher overall hydrogen feed to achieve target conversion, whereas well-designed quench zones enable optimal hydrogen utilization at lower flow rates.

## 6.2 Pressure Drop Considerations

Pressure drop across quench devices represents both an **energy penalty and operational limitation**. Excessive ΔP increases the load on hydrogen compressors, raising operational costs and potentially limiting turndown flexibility.

- **Early designs:** Baffled-box mixers typically incur pressure drops of 0.1–0.2 bar, while vortex mixers range from 0.05–0.15 bar.
- **Modern designs:** Multi-zone distributors and UOP swirl chambers reduce ΔP to 0.03–0.08 bar, balancing effective mixing with minimal energy penalty.

The ability to minimize pressure drop while maintaining turbulence and hydrogen distribution is a hallmark of advanced quench-mixing designs, illustrating the **trade-off between mechanical energy input and mixing efficiency**.

## 6.3 Scalability and Reactor Diameter

Large-diameter hydroprocessing reactors (≥3–5 m) present challenges in maintaining uniform phase distribution. Device design must ensure consistent quench performance across the reactor cross-section:

- **Vortex and impingement devices** are adequate for small-to-medium reactors but often struggle to deliver uniform mixing at larger scales.
- **Multi-zone and UFQ systems** incorporate multiple sub-chambers, swirl vanes, and subsurface injection to maintain both thermal and hydrogen uniformity in industrial-scale reactors.

Scalability is directly linked to **hydrogen utilization efficiency**. In large reactors, poor mixing increases the risk of bypassing and underutilized hydrogen. Advanced designs reduce this risk, lowering hydrogen feed requirements for a given conversion.

## 6.4 Fouling and Maintenance

Fouling and coking within quench zones reduce both thermal and mass transfer performance over time. Devices with **stagnant zones, sharp corners, or complex internals** are particularly susceptible.

- **Early designs** (baffled-box, impingement devices) required frequent maintenance due to scaling and coking.
- **Modern designs** (UFQ, Chevron Multi-Zone) use streamlined flow paths, swirl vanes, and subsurface injection to reduce dead zones, maintaining consistent hydrogen distribution over extended operational periods.

By minimizing fouling, advanced quench devices sustain both catalyst performance and hydrogen utilization efficiency, reducing downtime and operational costs.

## 6.5 Turndown Flexibility

Industrial reactors often operate under varying feed rates and compositions. Quench devices must accommodate wide **turndown ratios** (e.g., 40–130%) without compromising mixing effectiveness.

- **Impact on hydrogen utilization:** At low flow conditions, ineffective mixing can produce hydrogen-starved zones. Advanced designs with multi-zone injection and swirl-enhanced flow maintain consistent hydrogen availability across a wide turndown range, reducing the need for excess hydrogen feed.

### 6.6 Comparative Qualitative Assessment

From an industrial perspective, quench-mixing devices can be evaluated along four interrelated axes: thermal uniformity, pressure drop, hydrogen utilization, and operational robustness:

| **Device Type** | **Radial ΔT (°C)** | **ΔP (bar)** | **Hydrogen Utilization** | **Operational Notes** |
|---|---|---|---|---|
| Vortex Mixer | 5–8 | 0.05–0.15 | Moderate | Risk of fallback, limited micro-scale mixing |
| Baffled-Box Mixer | 3–6 | 0.1–0.2 | Moderate | Fouling-prone, high ΔP |
| Impingement Device | 6–10 | 0.05–0.1 | Low-Moderate | Limited interfacial area, scaling issues |
| Annular Collision Mixer | 4–7 | 0.05–0.1 | Moderate | Sensitive to flow variation |
| Segregated-Phase Mixer | 3–6 | 0.05–0.12 | High | Controlled wetting, limited scalability |
| Vortex–Bubble Cap Hybrid | 3–5 | 0.08–0.15 | High | Enhanced vapor lift, complex fabrication |
| UOP Compact Quench Zone | 2–5 | 0.05–0.08 | High | Height reduction, swirl-enhanced mixing |
| Shell UFQ | 1–4 | 0.05–0.07 | Very High | Excellent ΔT control, fouling-resistant |
| Chevron Multi-Zone | 1–3 | 0.03–0.06 | Very High | Multi-zone, low ΔP, robust across turndown |

### 6.7 Industrial Lessons

Several key insights emerge from comparative performance evaluation:

1. **Thermal control is necessary but not sufficient:** Devices must also optimize hydrogen distribution to achieve cost-effective operation.
2. **Pressure drop and mixing trade-off:** Modern designs succeed in achieving low ΔP while maintaining high turbulence and hydrogen utilization.
3. **Multi-zone and swirl-enhanced designs dominate large-diameter reactors:** These configurations provide consistent performance, reduce fouling, and optimize hydrogen feed.
4. **Maintenance and fouling considerations directly impact hydrogen efficiency:** Devices that sustain performance over long operational periods ensure stable hydrogen utilization and reduced operational costs.

Industrial considerations for quench-mixing devices extend beyond simple temperature control. Modern reactors require devices that:

- Achieve uniform radial and axial thermal profiles.
- Minimize pressure drop and energy consumption.
- Maintain effective hydrogen distribution, minimizing excess feed.
- Resist fouling and support wide turndown operation.

These requirements underscore the critical role of quench-mixing devices not only in **reactor safety and product quality** but also in **hydrogen utilization efficiency**, directly impacting refinery economics. The performance of advanced designs such as **Shell UFQ and Chevron Multi-Zone Distributors** illustrates how integrated hydrodynamic and mass transfer engineering can deliver superior industrial outcomes.

# 7. Computational Modeling and CFD of Quench-Mixing Devices

The increasing complexity of modern quench-mixing devices has driven the widespread adoption of **computational fluid dynamics (CFD)** as a tool for design optimization, performance evaluation, and scale-up of hydroprocessing reactors. CFD enables detailed visualization and quantification of flow patterns, turbulence intensity, temperature distribution, and hydrogen mass transfer within complex geometries, which is often impractical or impossible to achieve experimentally at full scale.

## 7.1 Role of CFD in Quench-Mixing Design

CFD serves multiple purposes in the context of quench-mixing devices:

1. **Flow distribution analysis:** Predicts liquid and gas velocities, identifying potential bypass or dead zones.
2. **Thermal modeling:** Determines radial and axial temperature gradients across the quench zone and downstream catalyst bed.
3. **Turbulence quantification:** Evaluates turbulent kinetic energy, eddy dissipation, and mixing scales.
4. **Hydrogen distribution and mass transfer:** Computes local hydrogen concentration and interfacial mass transfer rates (k_La), providing insight into hydrogen utilization efficiency.
5. **Design optimization:** Facilitates virtual testing of nozzle configurations, swirl vanes, baffle spacing, and injection angles without costly pilot-scale experiments.

By integrating these analyses, CFD allows engineers to **predict both thermal and chemical performance**, guiding design choices that balance pressure drop, mixing intensity, and hydrogen efficiency.

## 7.2 Multiphase Modeling Approaches

Quench-mixing in trickle-bed reactors involves simultaneous liquid and gas flows, often with variable flow rates and co-current or counter-current configurations. CFD employs multiphase modeling strategies to capture these phenomena:

- **Euler–Euler (two-fluid) approach:** Treats both phases as interpenetrating continua, solving conservation equations for mass, momentum, and energy for each phase. Suitable for dense, distributed flows where phase interaction is continuous.
- **Euler–Lagrange approach:** Tracks discrete liquid droplets or gas bubbles through a continuous phase. Useful for simulating jet impingement, droplet breakup, and interfacial mass transfer.
- **Volume of Fluid (VOF) method:** Captures distinct gas–liquid interfaces, suitable for modelling atomization, coalescence, and jet breakup in quench devices.

Each approach offers trade-offs between **computational cost, resolution, and accuracy**. Large industrial-scale reactors often require hybrid strategies or localized high-resolution models for the quench zone, coupled with coarser models for the downstream catalyst bed.

## 7.3 Turbulence and Mixing Models

Turbulence modeling is central to predicting mixing efficiency in quench devices. Several models are employed depending on desired fidelity:

- **Reynolds-Averaged Navier–Stokes (RANS):** Commonly used for industrial designs due to lower computational cost. Models like k–ε or k–ω capture mean turbulence effects but may underpredict small-scale eddies critical for micro-scale hydrogen mass transfer.
- **Large Eddy Simulation (LES):** Resolves large turbulent structures directly while modeling smaller scales. LES provides detailed insight into vortex formation, jet impingement, and eddy diffusion but is computationally intensive.
- **Detached Eddy Simulation (DES) or hybrid RANS-LES:** Combines RANS in regions of attached flow with LES in separated or high-turbulence regions, balancing accuracy and computational feasibility.

Accurate turbulence modeling is essential for predicting **radial ΔT, eddy diffusion, and hydrogen distribution**, particularly in multi-zone and swirl-enhanced quench designs.

## 7.4 Hydrogen Mass Transfer and Interfacial Modeling

Hydrogen utilization depends on the rate of mass transfer from the gas phase into the liquid hydrocarbon. CFD integrates mass transfer models to predict local hydrogen concentration:

- **k_La modeling:** The local volumetric mass transfer coefficient is computed based on turbulence intensity, droplet or bubble size, and residence time. High k_La correlates with improved hydrogen utilization.
- **Species transport equations:** Simulate hydrogen diffusion and convection throughout the quench zone and downstream catalyst bed.
- **Phase interaction models:** Capture bubble breakup, coalescence, and jet atomization, which enhance interfacial area and hydrogen absorption.

CFD enables **qualitative and quantitative prediction of hydrogen utilization**, allowing designers to identify underperforming regions and optimize device geometry accordingly.

## 7.5 Design Optimization Using CFD

CFD serves as a virtual laboratory for design iteration:

1. **Nozzle configuration and injection velocity:** Simulations can determine the optimal jet angles and velocities to maximize mixing while minimizing pressure drop.
2. **Swirl vane and baffle design:** CFD identifies vortex structures and dead zones, guiding modifications that improve turbulence and hydrogen distribution.
3. **Multi-zone integration:** Virtual testing evaluates how sequential quench zones equilibrate temperature and hydrogen concentration, informing chamber spacing and subsurface injection strategies.
4. **Scale-up:** CFD allows exploration of diameter effects on mixing, providing confidence in scaling laboratory or pilot designs to industrial reactors without costly experiments.

## 7.6 Limitations of CFD

Despite its advantages, CFD has inherent limitations:

- **Computational cost:** High-fidelity multiphase LES simulations for industrial-scale reactors are extremely resource-intensive.
- **Modeling assumptions:** Turbulence closure models, wall functions, and phase interaction parameters may deviate from reality, requiring validation against pilot or industrial data.
- **Simplifications:** Material properties, reaction kinetics, and fouling are often idealized, limiting predictive accuracy for long-term operation.

Hence, CFD is best employed in combination with **experimental validation**, including cold-flow testing, pilot-scale experiments, and operational data from existing units.

### 7.7 Industrial Insights from CFD Studies

CFD has provided actionable insights for quench-mixing design:

- Identifying **dead zones and short-circuiting regions**, allowing targeted design modifications.
- Optimizing **multi-zone configurations** to achieve radial ΔT < 3°C and consistent hydrogen distribution.
- Quantifying the relationship between **turbulence intensity and hydrogen mass transfer**, guiding nozzle, swirl vane, and baffle design for improved hydrogen efficiency.
- Supporting **retrofit decisions**, enabling older units to achieve performance comparable to modern designs without complete replacement.

By integrating CFD into the design process, refiners can **reduce hydrogen consumption, maintain consistent conversion, and minimize operational costs**, demonstrating the synergy between simulation and practical reactor operation.

CFD has become an indispensable tool for **design, optimization, and scale-up of quench-mixing devices**. Through multiphase modelling, turbulence analysis, and mass transfer evaluation, CFD provides insights into:

- Flow distribution and turbulence patterns.
- Radial and axial temperature uniformity.
- Hydrogen dissolution and utilization efficiency.
- Design optimization for pressure drop, fouling mitigation, and operational flexibility.

While computationally intensive and requiring careful validation, CFD enables **quantitative and qualitative understanding of complex quench-mixing phenomena**, directly linking device design to **thermal control, hydrogen efficiency, and refinery economics**.

## 8. Areas of Improvement and Future Directions

Despite significant advancements in quench-mixing technology, ongoing refinements are essential to meet the increasingly stringent requirements of modern hydroprocessing reactors. The performance of quench devices directly affects **hydrogen utilization, thermal management, and operational flexibility**, and continuous innovation is necessary to optimize both process efficiency and cost-effectiveness.

### 8.1 Early-Stage Mixing Enhancement

One persistent challenge in large-diameter reactors is achieving effective mixing immediately after quench injection:

- **Problem:** Inadequate initial turbulence can lead to local hotspots and hydrogen-deficient zones, reducing overall conversion and forcing higher hydrogen feed.
- **Potential improvements:** Development of **high-velocity micro-jet injection systems**, advanced swirl vanes, or impulse plates can generate **intensive initial momentum-driven mixing**, accelerating thermal equilibration and hydrogen dissolution.
- **Impact:** Enhanced early-stage mixing reduces ΔT spikes, minimizes hydrogen bypass, and supports consistent catalyst activity across the bed.

### 8.2 Modular and Multi-Zone Designs

Modern reactors demand **flexible, scalable quench solutions**:

- **Modular designs** allow easy retrofitting of existing units, enabling gradual upgrades without full shutdowns.
- **Multi-zone architectures** with sequential injection and flow conditioning improve stepwise thermal and hydrogen equilibration.

- **Research directions:** Optimization of sub-chamber geometry, baffle positioning, and swirl vane orientation using CFD and pilot testing can further enhance hydrogen utilization and pressure drop performance.

## 8.3 Fouling Mitigation and Material Selection

Fouling and coking remain key operational challenges that reduce both mixing efficiency and hydrogen availability:

- **Advanced coatings and materials:** Use of fouling-resistant alloys, ceramic liners, or surface coatings can minimize deposition and maintain long-term hydraulic and mass transfer performance.
- **Self-cleaning geometries:** Streamlined flow paths and surfaces designed to reduce stagnant zones can limit coking.
- **Impact on hydrogen utilization:** Reduced fouling maintains consistent gas–liquid contact, preventing hydrogen starvation and reducing excess hydrogen feed.

## 8.4 Smart Monitoring and Automation

Integration of sensors and automated control systems offers a pathway to **dynamic optimization of quench operation**:

- **Temperature, flow, and hydrogen sensors** embedded in the quench zone allow real-time monitoring of thermal and phase distribution.
- **Control strategies:** Automated adjustment of injection velocities, nozzle orientation, or quench flow rates can maintain optimal mixing across varying feed rates and compositions.
- **Industrial benefit:** Smart systems reduce human intervention, prevent hydrogen overfeed, and improve overall reactor efficiency.

## 8.5 Additive Manufacturing and Optimized Geometries

Advances in **3D printing and additive manufacturing** open possibilities for geometrically complex, high-performance quench devices:

- **Customized swirl chambers, baffles, and injection nozzles** can be fabricated with optimized curvature and spacing for enhanced turbulence and mass transfer.
- **Topology optimization:** CFD-guided design can identify optimal flow paths that maximize hydrogen dissolution while minimizing pressure drop.
- **Impact:** These approaches enable **next-generation devices** with high hydrogen utilization efficiency, lower $\Delta T$, and reduced fouling potential.

## 8.6 Wide Turndown and Flexible Operation

Refineries increasingly operate under **variable feed rates, compositions, and product slates**, requiring quench devices capable of maintaining performance across a wide operating envelope:

- **Design strategies:** Multi-zone injection, adjustable nozzle geometry, and swirl-enhanced flow can maintain uniform mixing under low-flow or high-flow conditions.
- **Hydrogen utilization implication:** Maintaining consistent hydrogen availability across turndown conditions reduces the need for excess hydrogen feed, contributing to operational cost savings.

## 8.7 Integration with Hydrogen Management Strategies

Quench devices play a critical role in **overall hydrogen efficiency** in the refinery:

- By ensuring uniform hydrogen distribution, they minimize **localized hydrogen starvation** and allow **optimized hydrogen feed rates**.

- Advanced quench-mixing designs can be coupled with **hydrogen recycle and recovery systems** to further reduce net hydrogen consumption.
- Future research could focus on **integrating quench design with hydrogen utilization modeling** to quantify cost savings and optimize reactor economics.

### 8.8 Future Research Directions

Key areas for ongoing research and development include:

1. **High-fidelity multiphase CFD validation** to improve predictive accuracy for industrial-scale reactors.
2. **Enhanced mass transfer surfaces** within swirl chambers and injection systems for faster hydrogen absorption.
3. **Adaptive quench systems** capable of dynamically responding to changes in feed composition, flow rate, or catalyst activity.
4. **Hybrid designs** combining momentum-driven mixing, eddy diffusion, and gas–liquid interfacial enhancements in a compact footprint.
5. **Material and coating innovations** to reduce fouling, coking, and maintenance frequency.

By pursuing these directions, quench-mixing technology can continue to evolve, delivering **higher hydrogen utilization, reduced energy consumption, and improved reactor performance**, while supporting the operational flexibility and economic efficiency demanded by modern hydroprocessing refineries.

Future improvements in quench-mixing devices focus on:

- Enhancing **early-stage turbulence** to prevent hotspots and hydrogen starvation.
- Implementing **modular, multi-zone architectures** for scalable and flexible operation.
- Reducing fouling and maintenance through **advanced materials and geometries**.
- Integrating **smart monitoring and automated control** for real-time optimization.
- Leveraging **additive manufacturing** to create complex, high-performance internals.
- Ensuring **wide turndown operation** with consistent hydrogen utilization.

Collectively, these innovations represent the next generation of quench devices, emphasizing **thermodynamic control, hydrogen efficiency, and operational resilience**, directly linking device design to refinery economics and environmental sustainability.

## 9. Conclusions

Quench-mixing devices are fundamental to the safe, efficient, and economically optimized operation of multi-bed trickle-bed hydroprocessing reactors. Their evolution reflects the continuous pursuit of **thermal uniformity, effective phase distribution, and enhanced hydrogen utilization**, which directly impact reaction kinetics, catalyst performance, and refinery economics.

From the early vortex mixers and baffled-box designs of the 1970s and 1980s to modern multi-zone distributors and ultra-flat quench (UFQ) systems, quench devices have progressively integrated **momentum-driven mixing, turbulent eddy diffusion, and interfacial mass transfer** to achieve superior performance. Modern designs, such as Chevron's Multi-Zone Distributor and Shell's UFQ, exemplify this evolution by delivering **radial temperature uniformity as low as 1–3°C**, minimal pressure drop, fouling resistance, and consistent hydrogen distribution across large-diameter reactors. Key Insights are as followings:

1. **Thermal and Hydrodynamic Control:** Effective quench-mixing prevents hotspot formation, minimizes catalyst deactivation, and maintains consistent reaction conditions, which are critical for selectivity and product quality.
2. **Hydrogen Utilization Efficiency:** By promoting uniform hydrogen dissolution and preventing local starvation, well-designed quench devices reduce excess hydrogen feed requirements, lowering operating costs and enhancing sustainability.

3. **Industrial Considerations:** Pressure drop, fouling resistance, scalability, and turndown flexibility are pivotal for reliable operation. Modern multi-zone and swirl-enhanced designs achieve an optimal balance of these factors, outperforming earlier single-zone or simple geometries.
4. **Computational Modeling and CFD:** CFD has emerged as an indispensable tool for understanding complex flow patterns, turbulence, and gas–liquid mass transfer. Coupled with experimental validation, CFD allows virtual optimization of nozzle geometry, swirl vanes, baffle placement, and multi-zone arrangements, improving hydrogen utilization and thermal performance without extensive pilot-scale testing.
5. **Future Directions:** Further enhancements focus on **early-stage mixing, modular multi-zone designs, fouling-resistant materials, smart sensors, adaptive control, and additive manufacturing**. These innovations will enable reactors to maintain high thermal uniformity and hydrogen efficiency under varying feed conditions, extending operational flexibility and reducing energy and hydrogen costs.

The article underscores that **quench-mixing devices are no longer just auxiliary thermal control elements**; they are integral to reactor design, influencing hydrogen consumption, operational costs, and process efficiency. The evolution of design principles—from simple momentum-driven devices to sophisticated multi-zone, swirl-enhanced systems—demonstrates the critical interplay between hydrodynamics, mass transfer, and process economics.

As refineries face increasing demands for **energy efficiency, reduced hydrogen consumption, and operational flexibility**, the continued development of advanced quench-mixing technologies will be pivotal. Future designs that integrate **high-fidelity CFD modeling, material innovations, and smart control strategies** are poised to set new benchmarks in hydroprocessing performance, ensuring safe and economical solutions.

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