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**REVIEW**

# A Comprehensive Review of the Influence of Heat Exchange Tubes on Hydrodynamic, Heat, and Mass Transfer in Bubble and Slurry Bubble Columns

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## ABSTRACT

Bubble and slurry bubble column reactors (BCRs/SBCRs) are used for various chemical, biochemical, and petrochemical applications. They have several operational and maintenance advantages, including excellent heat and mass transfer rates, simplicity, and low operating and maintenance cost. Typically, a catalyst is present in addition to biochemical processes where microorganisms are used to produce industrially valuable bio-products. Since most applications involve complicated gas-liquid, gas-liquid-solid, and exothermic processes, the BCR/SBCR must be equipped with heat-exchanging tubes to dissipate heat and control the reactor's overall performance. In this review, past and very recent experimental and numerical investigations on such systems are critically discussed. Furthermore, gaps to be filled and critical aspects still requiring investigation are identified.

## KEYWORDS

Fischer-tropsch synthesis; bubble/slurry bubble column reactors; heat exchanging tubes; hydrodynamic; heat transfer; mass transfer

## Nomenclature

|      |   |
|------|---|
| XTL  | “Natural gas, coal and biomass” to “Liquid” |
| GTL  | Gas to Liquid                               |
| BTL  | Biomass to Liquid                           |
| CTL  | Coal to Liquid                              |
| WTL  | Waste to Liquid                             |
| FTS  | Fischer Tropsch Synthesis                   |
| CFD  | Computational Fluid Dynamic                 |
| CSA  | Cross Section Area                          |
| BCR  | Bubble Column Reactor                       |
| SBCR | Slurry Bubble Column Reactor                |
| 2D   | Tow dimension                               |
| DPM  | Dynamic Pressure Method                     |



|                 |  |
|-----------------|--|
| RCFD            | Recirculation and Cross Flow with Desperation                  |
| H/D             | Height of dynamic liquid/Column diameter                       |
| L/D             | Height of column/Column diameter                               |
| Dc              | Bubble column diameter, m                                      |
| Hc              | Bubble column height, m  |
| Di              | Internal diameter, m   |
| D <sub>o</sub>  | Outer diameter, m  |
| U <sub>g</sub>  | Superficial gas velocity, m.s <sup>-1</sup>                    |
| k <sub>L</sub>  | Liquid-side mass transfer coefficient, s <sup>-1</sup>         |
| k <sub>La</sub> | Over all volumetric mass transfer coefficient, s <sup>-1</sup> |

## 1 Introduction

### 1.1 Energy Crisis and Environmental Impacts

Since fossil fuels are highly harmful to the environment, an alternative energy source must be discovered [1,2]. This alternative should be a sustainable and eco-friendly generation source that uses advanced techniques that reduce pollution, develop a long-term approach, and satisfy the world's energy consumption [2–4]. XTL technology is one of the essential technologies for obtaining low-carbon-emission fuels and chemicals from different raw materials, such as coal, natural gas, biomass, or waste [5,6]. Besides this method can convert solid biomass into liquid fuels, natural gas can also be processed with this technology into clean liquid fuels and chemicals [6–8].

Therefore, using XTL technology solves the problem of transporting and marketing natural gas worldwide. Various processes for producing liquid hydrocarbons from non-oil feedstock have been intensively developed over the past years and are still under research and development. These processes, including indirect technologies such as GTL (gas to liquids), CTL (coal to liquids), BTL (biomass to liquids), and WTL (waste to liquids), are examples of such processes [9–11]. These processes begin with the oxidizing conversion of carbon-containing feedstock to obtain synthesis gas, a mixture of carbon monoxide and hydrogen [9,12].

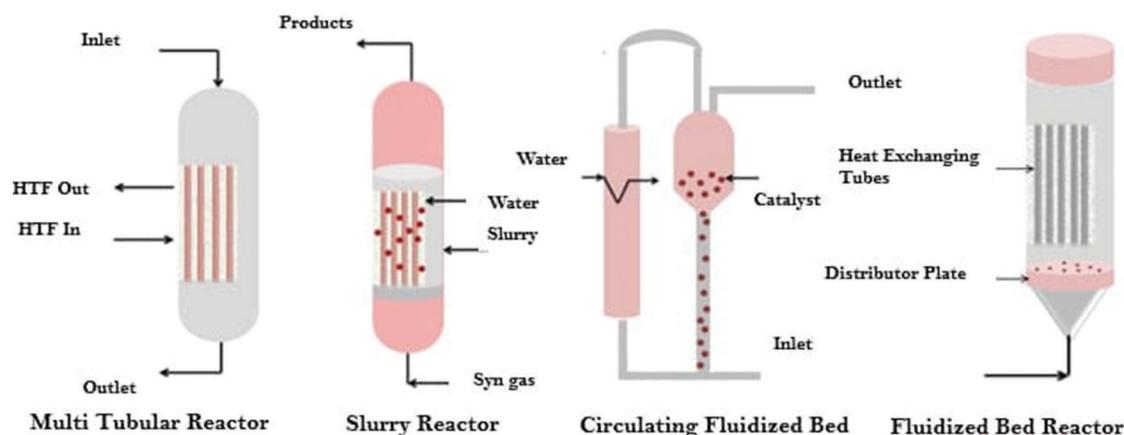
The XTL technologies include catalytic liquefaction, gas-reforming, gasification, water-gas shift converting, syngas-cleaning, methanol-synthesis, Fischer-Tropsch synthesis, and syn-crude refining [5,13,14]. The second step in most XTL processes is the Fischer-Tropsch synthesis, which creates hydrocarbons from carbon monoxide and hydrogen. Because it controls the production, content, and manner of refining hydrocarbon products, this stage of the XTL technology is crucial [15–17].

### 1.2 Fischer-Tropsch Synthesis (FTS)

FTS is a chemical synthesis process that transforms syngas (i.e., H<sub>2</sub> and CO) into synthetic liquid fuels and valuable compound chemicals. Thermal gasification of natural gas, biomass and coal is a practical technology for generating syngas from complex materials, especially those inferred from waste that is not economically feasible to handle for use in bio-catalytic and other rapidly progressive catalyst processes. Developing a newer catalyst with excellent selectivity and activity is desired since it increases the value and performance of FTS products [13,18].

Fischer-Tropsch synthesis is a major chemical process in manufacturing liquid fuels and olefins. The availability of natural gas in recent years and the rising demand for olefins, gasoline, diesel, and waxes have ignited a strong interest in further developing this process [19]. Moreover, FTS is an advanced liquefaction method for solid biomass or natural gas [5,20]. It enables liquid fuel production from different raw materials by catalytic conversion of the synthesis gas (i.e., a mixture of H<sub>2</sub> and CO) [21,22].

Controlling heat transfer in FTS is a crucial step since FTS is a highly exothermic process and occurs under high reaction temperatures resulting in increased methane output, carbon deposition, and catalyst deactivation [14,23]. This conversion is carried out in many multiphase reactors, including fluidized bed reactors, fixed bed reactors, and BCR-SBCR, as shown in Fig. 1 [24–28].



**Figure 1:** Illustration of Fischer-Tropsch reactors

The fluidized bed and fixed bed reactors are primarily utilized for highly-temperature FTP among these multiphase reactors. In contrast, the BCRs-SBCRs are typically used in low-temperature FTP. BCR-SBCR has been the most preferred reactors for FTS, according to their simplicity of manufacture, providing high interfacial area between reactants materials, offering a high rate of mass and heat transfer, and plug-free operating [29,30].

## 2 Bubble Column Reactor (BCR) and Slurry Bubble Column (SBCR)

In chemical, biochemical, and petrochemical applications, BCs are commonly used as multiphase reactors [31–34]. This type of reactor has various advantages, including, excellent heat and mass transfer rates, good thermal stability, inexpensive operating costs, and low upkeep requirements. Several variables affect the BC reactor's efficiency, which also influences the FTS, such as operating parameters (i.e., the physical properties of reactant materials, pressure, temperature, gas and liquid superficial velocities, operating mode, design parameters (i.e., height and diameter of the column and gas distributor design)) [35–37]. It is important to mention that the gas sparger is commonly positioned before the gas distributor plate at the bottom of the column, dispersing the gas phase as bubbles into liquid or suspension [6,38,39].

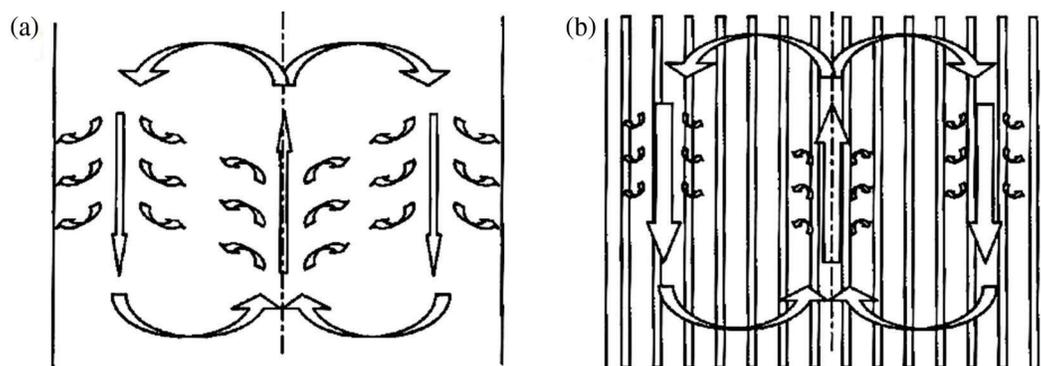
In almost all SBCR applications, fine solid particles (catalytic) are suspended in a gas-liquid system to catalyze reactions. For handling exothermic reactions by these reactors, heat exchanger tubes must be installed in the BCRs-SBCRs to dissipate heat, control operating temperature and hence regulate the reactor's performance [40]. Many theoretical and experimental studies have been conducted to facilitate the design, scaleup, and enhancement of these reactors' performance. However, these studies were conducted in BCRs-SBCRs that were not equipped with a bundle of heat-exchanging tubes despite these reactors being widely used for handling exothermic reactions that require dissipation for the heat generated. Accordingly, the impact of installing a bunch of cooling tubes on the hydrodynamic, heat, and mass transfer of BCR-SBCR is lacking in the literature and still needs to be better understood. A better understanding of the effect of these heat-exchanging tubes can be achieved by conducting comprehensive studies on these reactors when equipped with a bundle of heat-exchanging tubes.

Therefore, this review aims to critically discuss the previous and latest experimental and numerical studies on BCR-SBCR fitted with tubes. Moreover, it analyzes and reports the influence of equipping the

BC-SBC with tubes on hydrodynamics, heat, and mass transfer phenomena. Furthermore, it identifies the gap in the literature in this field and establishes further recommendations for future works.

### 3 Experimental Hydrodynamic Studies on BC-SBC Equipped with a Bundle of Heat Exchange Tubes

Heat exchange tubes have been commonly used in BCR-SBCR to eliminate excess heat and optimize operating conditions by influencing reactant phase distributions; the inclusion of cooling tubes has a major impact and influences fluid dynamics [41,42]. To increase mass/heat transfer rates in these reactors, the design of these cooling tubes must be enhanced. Therefore, it is essential to understand and comprehend the impact of cooling tubes and their configurations on the phase distribution of reactants material. Forret et al. [43] explored mixing liquid and dispersion in a 1 m diameter BC with and without a bunch of vertical tubes using a standard tracer technique. Also, they evaluated one dimensional-axial dispersion model (ADM) that can describe the level of back-mixing and measure the departure from the optimal behavior of plug flow on the column without internals [44,45]. Their study established two-dimensional models to consider internals when calculating the effect of liquid mixing at various superficial gas velocities. The bundle covered 22% of the column's CSA in this study. Their findings show that the insertion of vertical tubes has an impact on both local and large-scale liquid dispersion. In addition, they found that vertical tubes have the primary effect of reducing radial-dispersion and increasing large-scale recirculation, as illustrated in Fig. 2.



**Figure 2:** Illustration of liquid recirculating in BC (a) in the absence of vertical tubes (b) with vertical tubes [43]

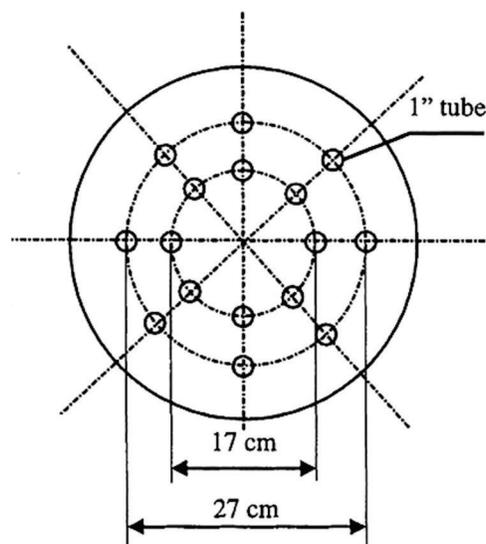
Zhang et al. [46] investigated two SBCs with 0.5 m diameter. The first one was equipped with vertical internals that blocked 11% (i.e., 40 vertical internals) of the column's CSA. The other column had vertical internals that equipped 5.3% (i.e., 18 vertical internals) of the CSA. The experiment results demonstrated that the vertical internals would significantly improve gas holdup (i.e., the volume percentage of gas in the overall volume of the gas-liquid phase in the bubble column). It is one of the essential parameters for characterizing the bubble column's hydrodynamic factors. It is closely related to bubble size and surface gas velocity with large-scale liquid circulation while inhibiting the radial dispersion of both liquid and bubbles.

Youssef et al. [47] measured the local-gas holdup and bubble characteristics (i.e., bubble chord lengths, bubbles velocities distribution, and gas-liquid interfacial area) in the BC fitted with a bunch of vertical rods by utilizing four tips optical probe at various operating superficial gas velocities. Their experimental investigation was conducted in two BC equipped with different occluded CSA by vertical rods. The first column has a bunch of vertical rods that block 5% of the CSA of the column to represent methanol synthesis. In comparison, the second column was equipped with vertical rods that blocked 22% of CSA

to simulate the FTP. Their research findings revealed that gas holdup and interfacial area were increased when the BC was equipped densely with rods (i.e., blocking 22% of CSA). In contrast, bubble chord lengths were significantly reduced. In addition, they found that when the BC was equipped with rods that covered 5% of CSA, the gas holdup and large-scale liquid circulation were negligible.

Chen et al. [27] used Computer Automated Radioactive Particle Tracking (CARPT) and Computed Tomography (CT) techniques to quantify the gas-liquid distribution, liquid recirculation, and turbulent stresses for a BC (0.44 m in diameter) equipped with a bunch of vertical rods.

These hydrodynamic parameters were measured at various operating superficial gas velocities. The bunch of vertical rods in their research was designed in a way to block 5% of the column's CSA to simulate the synthesis of methanol, as shown in Fig. 3. Their investigation showed a significant reduction in turbulent stress and a 10% increase in the gas holdup. Also, they discovered that the internals' existence does not affect the gas-liquid recirculation.



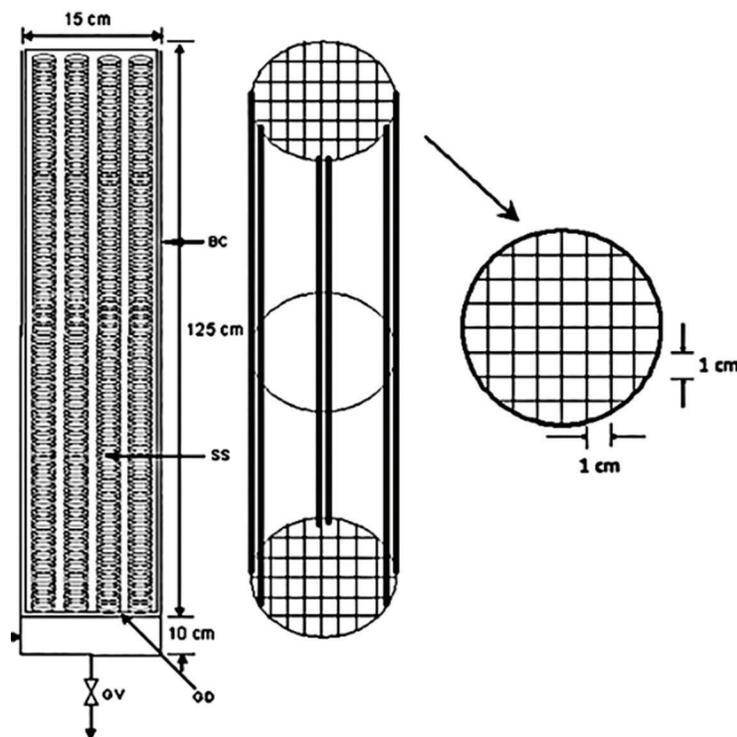
**Figure 3:** Configuration of a bundle of vertical rods [30]

Balamurugan et al. [48] examined the impact of using vibrating helical spring rods of various diameters and thicknesses on the total gas holdup in a BC with an inside diameter of 1.5 m at different superficial gas velocities varying from 3.6–54.2 cm/s. Fig. 4 shows the type and configuration of used vibrating helical spring rods. They used vertical rods for comparison purposes against vibrating helical spring rods. The experimental finding presented in their study indicates that gas holdup was enhanced up to 135% by utilizing vibrating helical spring rods in the BC reactor compared to empty BC reactors. They also indicated that the vibrating springs break up the gas bubbles into smaller bubbles, which reduces the gas's rising velocity and increases its residence time in the column.

Consequently, this method provides an easy, economical, and simple technique to improve gas holdup at a high gas flow rate. Despite using a novel design for vertical internals as shown previously, these studies were limited to measuring one parameter (i.e., overall gas holdup), which is a global parameter. Therefore, further investigations are needed to check the new design's visibility.

Among the simulation studies of a bubble reactor, Abid et al. [38] applied the Eulerian-Eulerian model in their simulation with a constant bubble size (CBSM) and variable bubble size modeling approach (VBSM). According to his work, the proposed approach and CFD-PBM modeling are used to simulate a lab-scale

bubble column operating in a heterogeneous regime, and the computing efficiency and accuracy of these two approaches are quantified. Furthermore, in CFD-PBM simulations, numerous combinations of bubble coalescence models and breakage models are employed to investigate the influence of coalescence and breakdown models on simulation outcomes. The effect of the minimum bubble diameter, a critical parameter of the discretization approach, is also investigated. It should be mentioned that the numerical models employed in the developed technique are the same as those used in CFD-PBM modeling, with the difference that the breakdown and coalescence models are not recognized in the developed method. A series of discrete points represent the range of bubble sizes, and the proportion of bubbles of various sizes at the gas inlet is obtained by the results of Computational fluid dynamic balance model (PBM) simulations, with the impact of bubble coalescence and breakup ignored [41,49–55].

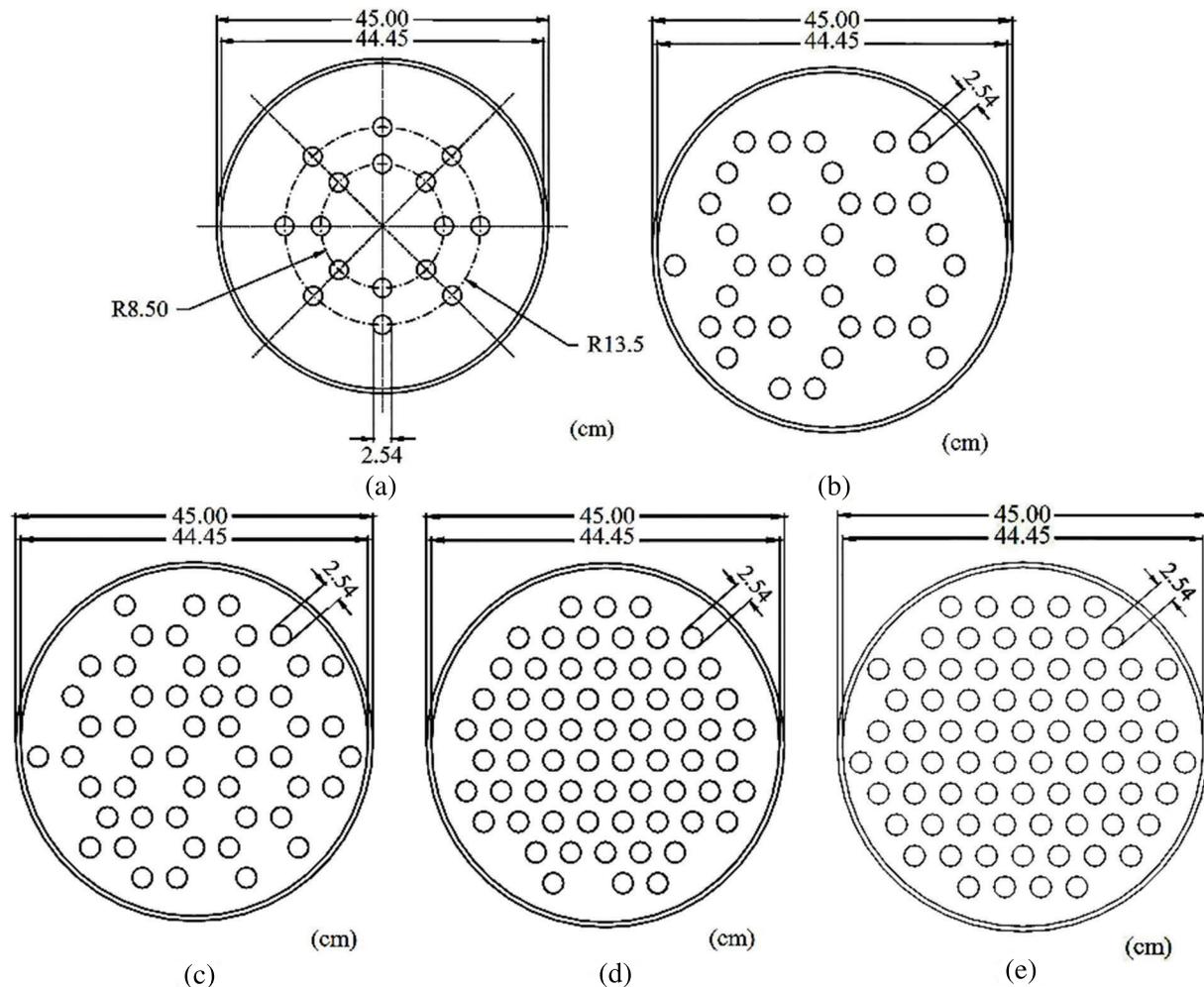


**Figure 4:** Bubble column schematic with spring rods [46]

Youssef et al. [56] continued the investigation in the field of the hydrodynamics of BCR with vertical internals. They experimentally characterized the bubble properties using an optical probe technique in a large-scale BC with a 0.45 m diameter fitted densely with a bundle of vertical rods at various superficial gas velocities ranging from 0.05–0.45 m/s. In their study, the bundle of rods was designed to cover 5%, 10%, 20%, and 25% of the column's total CSA, as presented in Fig. 5. Their experimental findings at different superficial gas velocities revealed that the vertical rods increased the overall gas holdup and changed the radial gas holdup profile. In addition, they discovered that the tube bundle's presence in a large-diameter column caused an improvement in liquid recirculation.

Kagumba et al. [57] studied the effects of vertical internals on the bubble characteristics in two BCRs with 0.14 and 0.44 m inner diameters using an optical sensor with four tips under operating superficial gas

velocity ranging between 0.03 and 0.45 cm/s. Two different configurations were used in this work. The first configuration was made of 30 Plexiglas rods of 2.54 cm in diameter, while the second configuration was made of 8 Plexiglas rods of 1.27 cm in diameter. The rods for both configurations were designed in a triangular pitch occupying 25% of the CSA targeting in their study of the FTP, as shown in Fig. 6. Their experimental findings revealed that the tubes with a diameter of 2.54 cm consistently provided better overall and local gas holdup than tubes with a diameter of 1.27 cm or an empty column. The internal diameter has little impact on the churn turbulent flow regime. Also, they indicated that local and overall gas holdup and bubble properties (bubble passage frequencies, bubble chord lengths, and axial bubble velocity) increase with increasing column diameter for BCR/SBCR with and without vertical internals.

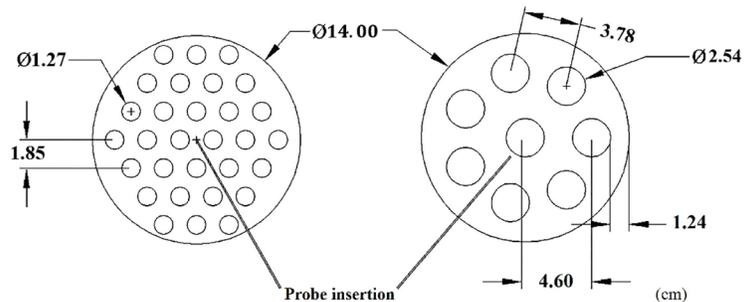


**Figure 5:** Bundle rods configurations covering (a) 5%, (b) 10%, (c) 15%, (d) 20%, and (e) 25% of the CSA [47]

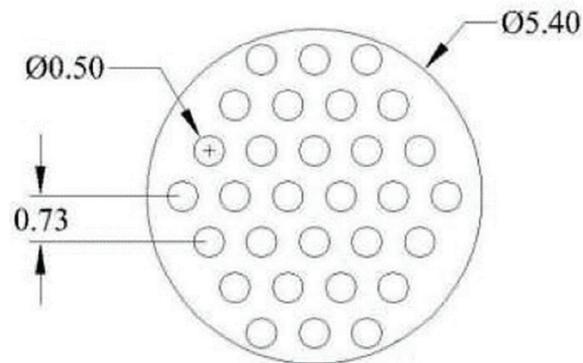
Al Mesfer et al. [58] examined the effect of inserting a bunch of vertical rods on the gas hold up in a BC with 0.14 m in diameter operated at various flow regimes (i.e., homogeneous and heterogeneous flow regimes) by utilizing gamma ray Computed Tomography (CT) technique. A triangular pitch of 30 vertical rods with a 1.27 cm outer diameter covering 25% of the CSA was used, as shown in Fig. 7. The research



showed that the vertical rods gradually increased the local and overall gas holdup. Other impressive effects were noticed, such as the influence of the vertical rods on the form of the gas holdup profiles close to the wall and that the effect of dense tubes became minor at high velocities. Furthermore, they observed that, when employing the same-sized tubes and the same occluded CSA, the vertical rod bundle had a substantial impact on gas holdup over the CSA of the column.



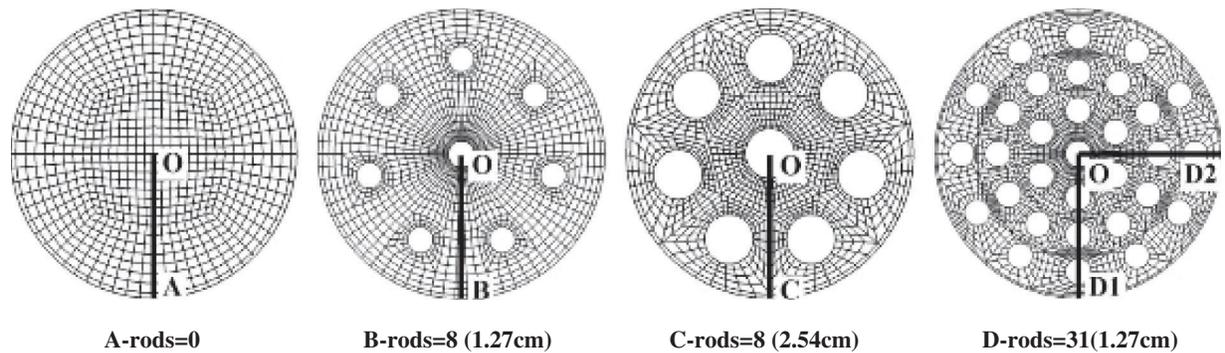
**Figure 6:** Rods arrangements for both sizes of rods [48]



**Figure 7:** Configuration of the vertical rods [59]

Al Mesfer et al. [59] continued studying the influence of inserting a bunch of vertical rods on the hydrodynamics of BC. They extended experimental work on the velocity of liquid and turbulence variables utilizing the Radioactive Particle Tracking (RPT) technique for the same BC. From experimental analyses, they deduced that the existence of vertical rods with increased superficial gas velocities causes an increase in both axial velocity and liquid centerline. On the other hand, they noticed a substantial reduction in turbulence parameters, whereas an increase in superficial gas velocity in the absence of internals leads to an increase in both. The data acquired from their research are very beneficial for computational fluid dynamics (CFD) simulations and model validation.

Guo et al. [60] simulated the impact of tube-bunch on the hydrodynamics of gas-liquid of BC with 0.14 m diameter under two operating gas flow rates (0.03 and 0.45 m/s). In their simulation, they utilized the dimensions of BC and the layout of vertical internals the same as that used by Kagumba et al. [61] and Al Mesfer et al. [62], as shown in Fig. 8. An Eulerian two-fluid model (TFM) and a population balance method (PBM) were utilized in their simulation. Also, the numerical simulations were conducted fully three-dimensional with ANSYS Fluent.



**Figure 8:** Geometric configurations of vertical rods [51]

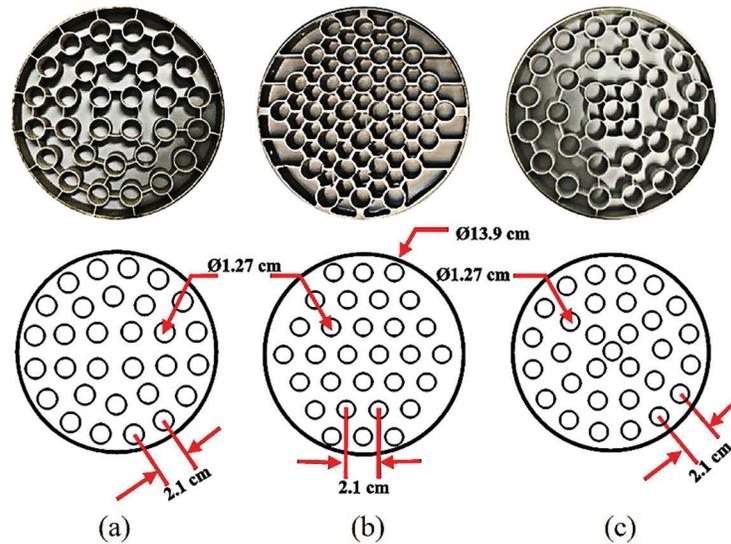
According to the simulation's findings, a BC with vertical rods included a greater number of smaller-sized bubbles. Also, they reported that the turbulent dissipation rates were dramatically elevated in the spaces between the internal walls, according to the numerical results.

Guan et al. [63] predicted the influence of the installation of a bunch of vertical rods on the hydrodynamic parameters of a pilot-scale BC (0.48 m in diameter) by using 2D CFD (a set of numerical modeling techniques to simulate and forecast the dynamics of single-phase and multi-phase fluid flows related to chemical reactions, hydrodynamics, heat and mass transfer with fundamental principles). In this research, the bundle rods were chosen to block 5% of CSA and arranged in equilateral triangular. Their CFD results show that a bundle of rods has no consequence on gas holdup, and it enhances large-scale liquid circulation by significantly reducing the turbulent velocity. Also, the findings indicate that the bunch of rods reduced the average bubble chord length in the BC while dramatically increasing turbulent dissipation rates in the spaces between the bunch rods and the column wall.

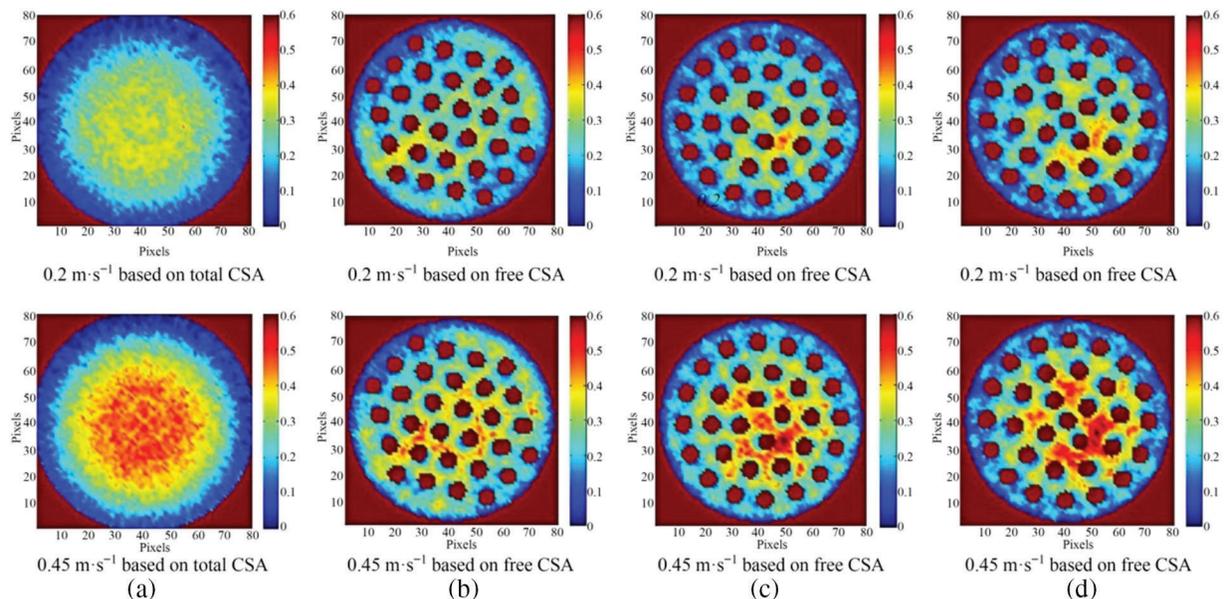
Sultan et al. [64] visualized and quantified in a noninvasive way the impact of inserting a bunch of vertical rods and the design of configurations of rods in a 0.14 m BC on gas holdup distribution utilized an advanced gamma-ray Computed Tomography (CT) technique. Three distinct configurations of vertical rods were designed and used in their experimental work, as shown in Fig. 9. Despite using different configuration designs in their work, the bunch of vertical rods was designed to occupy 22% of the column's CSA to simulate the cooling tubes used in the industrial FTP. Their CT images in Fig. 10 displayed that the hexagonal configuration led to a notable improvement in gas holdup values and enhanced distribution of the gas dispersed across the whole of the column's CSA. Gas holdup distribution was asymmetric in the BC, including circular tubes and an additional central tube. The obtained data of CT images for gas-liquid distribution throughout the whole CSA of a BC equipped densely with a bunch of vertical rods would be greatly helpful in developing and validating CFD simulation or even mathematical models. This validation process for simulation or models through benchmark data will advance this reactor's design and scale-up.

Al-Naseri et al. [29] measured the radial profiles of the bubble characteristics in a BC with a diameter of 0.6 m at superficial gas velocities ranging from 0.2 to 0.45 m/s by using four points of optical probes. Twenty-four tubes, each 0.06 m in diameter, were placed in a hexagonal configuration and inserted inside the column, occupying 24% of the CSA of the column shown in Fig. 11. Various available height levels of dynamic liquid to the diameter of the bubble column (aspect ratios H/D) were employed (H/D = 3, 4, and 5) in their experiments to quantify the effect of using different aspects ratio on the bubble properties.

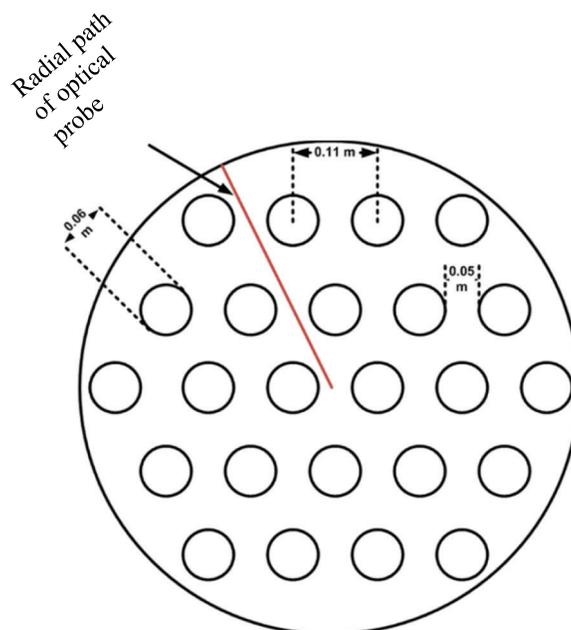
According to their findings, the tubes significantly impacted the distribution of bubble characteristics and radial profiles distribution, especially in the fully developed flow zone, and slightly increased overall gas holdup.



**Figure 9:** Picture and schematics for different configurations (a) circular, (b) hexagonal, (c) circular with an extra tube in the center [53]



**Figure 10:** CT images for gas holdup distribution measured in BC with and without vertical rods under a variety of operating superficial gas velocities [53]



**Figure 11:** Configuration of hexagonal rods [31]

In contrast, reduce the chord length of the bubble and velocities of the bubble rise while increasing both the interfacial bubble area and the bubble pass frequency, particularly at the wall zone. Furthermore, the existence of tubes and an increase in the aspect ratio ( $H/D$ ) indicate that the fully developing flow zone begins at lower axial locations. Also, an increase in superficial gas velocities conserves the change to a higher axial site.

The summary of investigations based on experiments carried out in SBCR and BCR with a bunch of tubes is described in Table 1. This table includes brief details about the effect of internals (heat exchange tubes) on hydrodynamics.

According to the above discussion of previous studies, a few studies have been done on the hydrodynamics of a bubble column equipped with a bundle of rods. These few studies have contributed a lot to improving the understanding of the effect of installing a tube bundle inside this reactor on the hydrodynamic factors. However, these studies have some limitations. Among these limitations, most previous studies were conducted at atmospheric temperature and pressure, while the real Fischer Tropsch synthesis (FTS) occurs at high temperature and pressure. Also, the past studies were limited to the air-water system, which does not represent the actual material involved in FTS. Moreover, all the bundles used in the previous studies were solid rods, not real heat exchanger tubes. Furthermore, all previous studies were not involved in any chemical reactions. Therefore, further research is required to enhance the fundamental understanding of the impact of inserting a heat exchanger inside these reactors on the hydrodynamics parameters, which affect the performance of these reactors and, ultimately, the productivity of FTS.

**Table 1:** Summary of studies on the influence of the existence of a bundle of vertical internals on the hydrodynamic of BCR-SBCR

| No. | Authors                  | System type   | Column dimensions<br>Dc Hc        | Superficial gas velocities<br>cm/s | Type of tube configurations  | Internals' influence   |
|-----|--------------------------|---------------|-----------------------------------|------------------------------------|--|--|
| 1   | Chen et al. 1999 [27]    | Air-drake oil | 44 cm<br>2.4 m                    | 2–10                               | Vertical heat exchange,<br>16 tubes ( $D_o = 25.6$ mm)   | <ol style="list-style-type: none"> <li>1. No influence on the gas-liquid recirculation pattern.</li> <li>2. Lower turbulence levels because of a smaller turbulence length scale.</li> <li>3. Significantly increased gas holdup.</li> </ol> |
| 2   | Forret et al. 2003 [43]  | Air-water     | 100 cm<br>3.7 m                   | 15                                 | Vertical internals,<br>56 tubes ( $D_o = 63$ mm)   | <ol style="list-style-type: none"> <li>1. Improved liquid recirculation and local dispersion</li> <li>2. Reduction of fluctuation velocity.</li> </ol>   |
| 3   | Larachi et al. 2006 [65] | Air-water     | 19 cm<br>1 m                      | 12                                 | Vertical bundle of heat-exchanging tube 31–131 tubes ( $D_o = 25.6$ mm)  | <ol style="list-style-type: none"> <li>1. Reduced in the liquid kinetic turbulence energy.</li> </ol>  |
| 4   | Youssef et al. 2009 [47] | Air-water     | 19 cm<br>2 m                      | 3–20                               | Vertical Plexiglas rods.<br>2 circles of six rods covering 5% of CAS, with $D_o = 8$ and 14 mm, 48 rods arranged in a triangular pitch of 2.4 cm, covered 22% of the CAS | <ol style="list-style-type: none"> <li>1. The interfacial area, liquid mixing, and gas holdup were increased.</li> <li>2. The bubble chords' length decreased.</li> </ol>  |
| 5   | Hamed 2012 [66]          | Air-water     | 19 cm<br>1.9 m<br>45 cm<br>2.66 m | 20–45                              | Vertical internals<br>12 tubes ( $D_o = 2.56$ mm)<br>48 tubes ( $D_o = 1.28$ mm)   | <ol style="list-style-type: none"> <li>1. Local and frequency turbulence flow, the mixing of the gas phases were reduced.</li> <li>2. The interfacial area and the gas velocity at the center have increased.</li> </ol>                     |

(Continued)

Table 1 (continued)

| No. | Authors                   | System type | Column dimensions<br>Dc Hc | Superficial gas velocities<br>cm/s | Type of tube configurations  | Internals' influence  |
|-----|---------------------------|-------------|----------------------------|------------------------------------|--|---|
| 6   | Jhawar et al. 2014 [67]   | Air-water   | 15 cm<br>2.5 m             | 3–35                               | Concentric baffle<br>15 tubes ( $D_o = 12.7$ mm)   | <ol style="list-style-type: none"> <li>1. Gas holdup and overall heat transfer increased.</li> <li>2. Bubble size and liquid velocity decreased.</li> </ol>   |
| 7   | George 2015 [68]          | Air-water   | 15 cm<br>2.5 m             | 1–30                               | Circular Tube Bundle<br>1. tubes (9.5 mm)  | <ol style="list-style-type: none"> <li>1. Gas holdup and interfacial area increased.</li> <li>2. As the liquid mix increases, the mixing time decreases.</li> </ol>   |
| 8   | Jasim 2016 [69–71]        | Air-water   | 14 cm<br>1.83 m            | 20–45                              | Plexiglas rods (heat exchanging tubes)<br>30 tubes ( $D_o = 12.8$ mm)<br>8 tubes ( $D_o = 25.6$ mm)  | <ol style="list-style-type: none"> <li>1. Smaller internals: increased core local holdup.</li> <li>2. Larger internals: the length of the bubble chord increases, resulting in a higher bubble velocity.</li> </ol>   |
| 9   | Agahzamn et al. 2019 [72] | Air-water   | 19 cm<br>1.6 m             | 1–20                               | Cylindrical rods cover 21.5 % of hexagonal internals.<br>48 tubes ( $D_o = 12.7$ mm)   | <ol style="list-style-type: none"> <li>1. Increased gas circulation with reduced turbulence and dispersion.</li> <li>2. Reduced the fluctuating liquid velocities, which had a negative impact on the bubble column's ability to mix.</li> </ol>  |
| 10  | Guan et al. 2021 [73]     | Air-water   | 15 cm<br>1.6 m             | 0.8–25                             | Helically finned tube (HFT) internals. 12 HFTs ( $D_o = 25$ mm) 4 bar tubes next to the column wall were vacant and separated from the Plexiglas wall. | <ol style="list-style-type: none"> <li>1. The bare rods promote the stability of 2 different flows, while the helical fins dismantle it.</li> <li>2. The distribution pattern of gas holdup and bubble size becomes more uniform in the existence of HFTs.</li> <li>3. Helical fins cause spiral movement, bubble accumulation, and increased flow resistance.</li> </ol> |

#### 4 Heat Transfer in BCR/SBCR Equipped with a Bunch of Vertical Tubes

In order to eliminate extra heat and maintain the proper operating conditions, heat exchange tubes are frequently installed in BCR-SBCR columns. One of the main difficulties in the FTP is the evacuation of significant amounts of the excessive heat produced by exothermic synthesis reactions to protect the catalyst from deactivation and poisoning. Heat generation that produces hot-spots and carbon deposits on the catalyst could cause this catalyst deactivation. Therefore, excess heat must be removed. Studying heat transfer coefficients (HTC) in BCR/SBCR may be helpful when designing, implementing, and augmenting production reactors. It is considered one of the vital factors in the way these reactors work. In gas/liquid and gas/liquid/solid systems, bubbles cause disturbs and mix gases, considerably improving heat/mass transfer. Therefore, bubble-induced turbulence is primarily responsible for the high HTC in the BCR/SBCR [57,61,74,75].

According to the literature on BCR/SBCR, there are tremendous studies on hydrodynamic, heat, and mass transfer in these reactors that are not equipped with a bunch of vertical rods. However, few experimental and numerical studies on BCR/SBCR fitted densely with many tubes. Furthermore, investigation of heat transfers in BCR/SBCR with a bunch of vertical tubes is even scarce. Among these heat transfer investigations:

Abdulmohsin et al. [76] investigated the impact of internals on the HTC in a 0.19 m diameter BC operating under superficial gas velocities ranging from 0.03 to 0.2 m/s by utilizing a fast response HT technique. They examined the effects of cooling tubes that covered 0% (an empty column), 5% (to simulate the synthesis of methanol), and 22% (to simulate the synthesis of FT) of the total CSA. Their study showed that the HTC was enhanced in the column, with a larger percentage of internals covering the CSA (22%).

Jhawar et al. [77] used a fast response probe in a BC with a 0.15 m diameter and operated it under various flow rates (0.03 to 0.35 m/s) to study the effect of vertical rods on the local HTC. Their experimental work was conducted with two types of vertical rods: fifteen tubes arranged in a circular pitch of 12.7 mm and six concentric baffles, as shown in Fig. 12. They found that the presence of the tube bundle enhances HTC in the central region compared to a hollowed BCR.

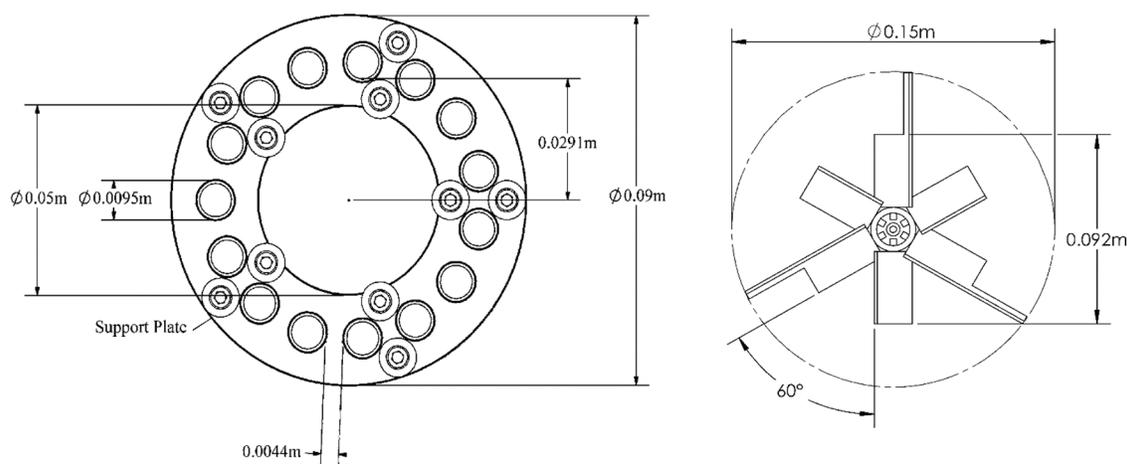
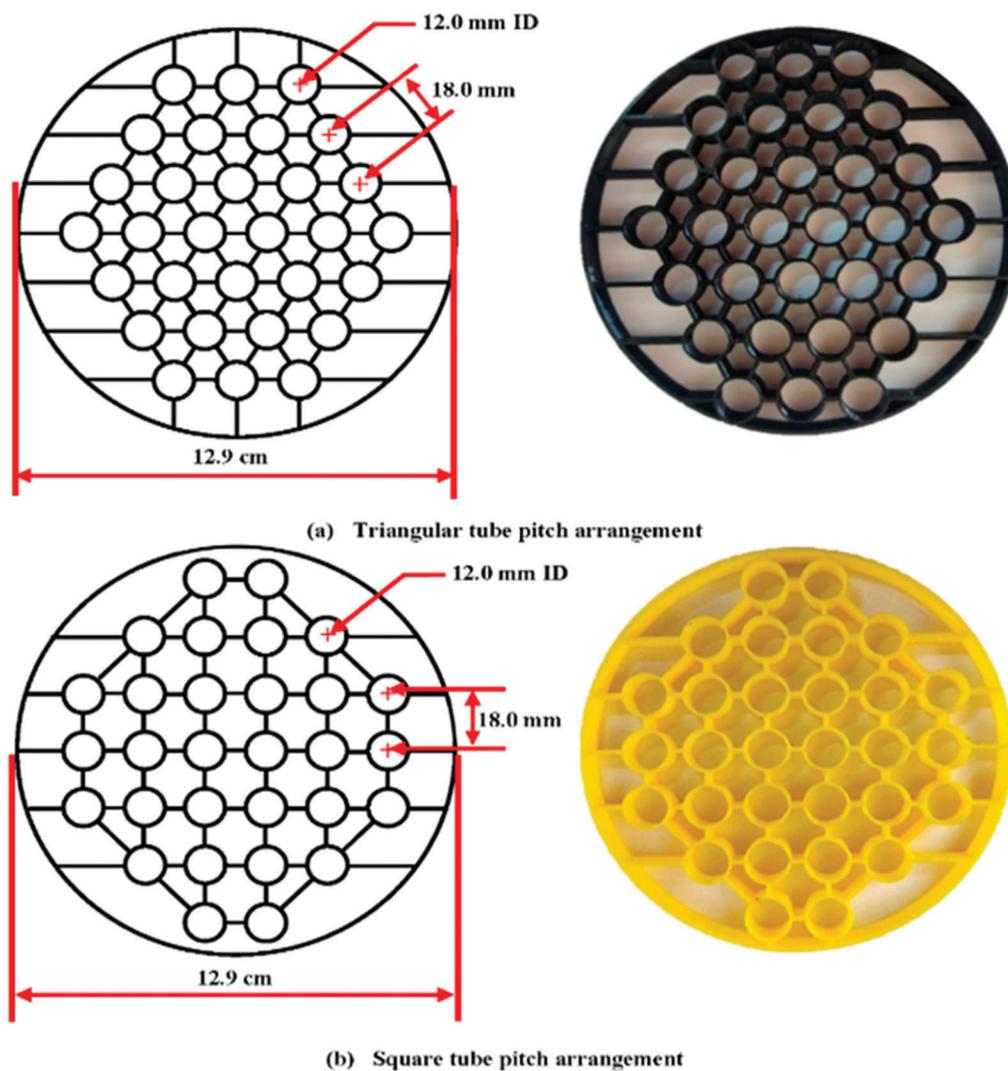


Figure 12: Design of vertical rods [66]

Jhawar et al. [78] studied the influence of inserting vertical rods inside the BCR on local HTC. This research investigated the local HTC in an SBCR with a 0.15 m diameter equipped with dense vertical internals. This study measured and quantified the influence of using various configurations (i.e., 15 tubes in a circular arrangement of 12.7 mm pitch and 6 concentric baffles) on local HTC at a wide variety of flow rates ranging from (0.03 to 0.35 m/s). He observed that the local HTC with a bundle of vertical internals was increased. Also, he found that the HTC decreased as slurry concentration increased.

Alzamily et al. [79] recently investigated the impact of equipping a BC with a bunch of tubes on instantaneous and local HTC radially and axially operated at a wide variety of gas flow rates ranging from (0.05–0.45 m/s) by using an advanced heat transfer technique. They examined different arrangement designs (square and triangular tube pitch configurations), as illustrated in Fig. 13.



**Figure 13:** Geometric layouts of square and triangular tubes [68]



**Table 2:** Summary of heat transfer studies on the influence of vertical internals in BCRs-SBCRs

| No. | Authors                      | System  | Column dimensions<br>Dc Hc   | Range of superficial gas velocities cm/s | Type of tube configurations  | Internals' influence   |
|-----|------------------------------|---|------------------------------|--|--|--|
| 1   | Saxena [80]<br>1991          | Nitrogen-Therminol 66-red iron oxide powder                 | 10.8 cm<br>not be defined    | 1.1–23.8                                 | 7 tubes of a bundle with a diameter of 19 mm   | <ol style="list-style-type: none"> <li>1. Internal tubes affect HTC, and their impact is related to liquid slurry circulation.</li> <li>2. HTC increased as nitrogen velocity increased for all internal configurations.</li> </ol>  |
| 2   | Westermeyer [81]<br>1992     | Air-water/<br>$C_2H_6O_2$<br>salt water/1,2-<br>$C_3H_8O_2$ | 12–45 cm<br>3.62–<br>6.68 m  | 1–60                                     | 36 Longitudinal tube of bundles with 15, 25 and 63 mm diameter                                       | <ol style="list-style-type: none"> <li>1. The heat transfer coefficient reduces as pitch diameter decreases.</li> <li>2. The heat transfer coefficient increases as the reactor diameter increases.</li> </ol>   |
| 3   | Taha et al. [82]<br>1993     | Air-water-glass beads                                       | 30.5 cm<br>3.3 m             | Up to 30                                 | 5, 7 and 37 stainless steel tubes of bundles of 19 mm diameter                                       | <ol style="list-style-type: none"> <li>1. The size and arrangement of the tube bundle have an impact on the HTC.</li> <li>2. HTC is independent of the bundle type since a bubble size is smaller than the tube bundle pitch.</li> <li>3. HTC depends on bubble dynamics, and the mix of the liquid they cause in the column since the size of the bubbles is similar to pitch.</li> </ol> |
| 4   | Muroyama et al. [83]<br>2003 | Air-water/CMC-glass beads                                   | 8.2–15 cm<br>1.88–<br>2.08 m | 0.9–15                                   | One cylindrical tube with a diameter 25 mm   | <ol style="list-style-type: none"> <li>1. It is established on the vertically inserted cylinders' column that mass and heat transfer are perfectly analogous.</li> <li>2. HTC increased substantially when the superficial gas velocities increased.</li> </ol>  |
| 5   | Béliard et al. [84]<br>2010  | Air-Syltherm XTL thermal oil                                | 15 cm<br>4.4 m               | 2–28                                     | Two U-shaped tubes made of stainless steel with $D_i$ and $D_o$ of 22.4 mm and 26.7 mm, respectively | <ol style="list-style-type: none"> <li>1. There may or may not be a substantial difference in the HTC for every U-tube part.</li> </ol>  |
| 6   | Odongo et al. [85]<br>2013   | Air-water-glass beads                                       | 14 cm<br>1.83 m              | 2–28                                     | Plexiglas rods of 12.7 mm and 25.4 mm diameter   | <ol style="list-style-type: none"> <li>1. The HTC enhanced with the insertion of dense internals.</li> </ol>   |
| 7   | Azamily et al. [79]<br>2022  | Air-water   | 13 cm<br>1.83 m              | 5–45                                     | 30 stainless steel tubes of bundles with 12 mm diameter  | <ol style="list-style-type: none"> <li>1. The HTC was improved with the configuration of the square tube.</li> </ol>   |

Additionally, the axial height's impact on HTC has been studied. According to their findings, HTC has a uniform-profile due to the square tube's pitch arrangement. Higher heat transfer values are attained towards the center of the column when equipped with a bundle of tubes. Also, this study showed that the configuration of the tubes has a considerable impact on the shape of the HTC profile. For instance, the triangular tube pitch arrangement induced a high HTC profile.

Heat transfer studies in BCRs/SBCRs with various vertical internal designs are summarized in [Table 2](#). Despite the importance of using a bundle of internals for industrial BCRs/SBCRs, previous literature on heat transfer studies in BCRs equipped with a bundle of vertical internals shows that understanding of the impact of these vertical internal tubes on heat transfer is still limited and lacking in the available literature.

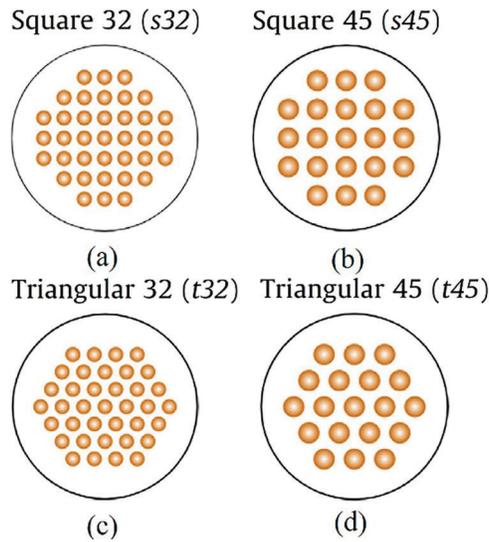
### 5 Mass Transfer Studies in BC-SBC with a Bunch of Vertical Tubes

One of the most crucial process variables in the fields of chemicals, petrochemicals, and biological engineering is the overall volumetric gas-liquid mass transfer ( $K_{La}$ ). It is an important design parameter for BC and SBC, especially in operations like the FTP and methanol synthesis that require absorbing gases into organic liquids. Since mass transfer has been studied over the past few years, experiment values and correlation for  $K_{La}$  at various operating parameters have been collected [66,86]. Unfortunately, these experimental studies were carried out in BCs without vertical tubes. Even though comprehensive efforts have been made in recent decades to help comprehend the mass transfer of BCRs and SBCRs, only a limited number of these experiments have been obtained in BC fitted with a bunch of internals on mass transfer. The following is a summary of the researchers' study in recent years on the impact of vertical internals on mass transfer in both BCs and SBCs.

Hamed [66] conducted and quantified the effect of vertical rods on the volumetric gas-liquid mass transfer coefficient,  $K_{La}$ ; and the gas-liquid mass transfer,  $KL$ ; in a pilot-scale BC 0.45 m diameter at a variety range of superficial gas velocities from 0.02 to 0.45 m/s, utilized the optical- oxygen probe and an oxygen-enriched air dynamics methods. According to his finding, the  $KL$  factor with a bunch of vertical internals was decreased compared with the case without internals from 0.047 to 0.032  $s^{-1}$ . Therefore, the interfacial-area increased. Also, he noticed that the value of  $K_{La}$  in the absence of internals ranged from 0.091 to 0.15  $cm/s$ , which is the same value in the presence of internals, indicating that the  $K_{La}$  values did not affect the inclusion of vertical internals.

Manjrekar et al. [87] studied the impact of vertical rods on the  $K_{La}$  and  $KL$  in two pilot-scale BC 0.45 and 0.19 m diameters in the air-water system using dynamic-gas separation technique to calculate the volumetric mass transfer coefficients. Their experimental findings showed that vertical rods had no discernible impact on the  $KL$  (0.03  $cm/s$ ) in the churn turbulent flow regime. Consequently, the decrease in mass transfer coefficients  $K_{La}$  (0.13  $s^{-1}$ ) caused by a decrease in turbulent intensity with the existence of internals is offset by an increase in gas-liquid interfacial- area which is caused by increased bubble separation.

Möller et al. [86,88] recently conducted a study examining the impact of two different tube arrangements (i.e., the triangular pitch of 0.032 m and square pitch of 0.045 m) with U-tube bottom end design on the  $K_{La}$  using an oxygen probe technique in the air-water system. They conducted their experiments in a pilot-scale BC with a diameter of 0.392 m equipped with a bundle of tubes (i.e., blocking 25% of CSA). The  $K_{La}$  was measured under different gas flow rates ranging from 0.01–0.2 m/s (i.e., covering the bubble and churn flow regimes). Both tube layouts and specifications are illustrated in [Fig. 14](#). From experimental work, the results from narrow and pilot-scale columns have been compared, deduced that internals reduces volumetric mass transfer approximately from (0.18 to 0.1  $s^{-1}$ ) and cause flow asymmetries which is consistent with Manjrekar et al. [87].



**Figure 14:** Tube arrangement inside the bubble column [86]

Möller et al. [89] later suggested a sophisticated recirculation-cell model conduct mass transfer in the same BC (0.39 m diameter) either with or without internals. The model, which assumed the size of the bubbles, was validated using Möller et al. [86] experimental data. Their experiment showed that the mass transfer rate decreased approximately from  $(1.7 \text{ to } 1.3 \text{ s}^{-1})$  when inserting a tube bundle of vertical internals.

Table 3 illustrates the summary investigations of the effect of a bunch of tubes based on experiments carried out in the BCR and SBCR on mass transfer. It was noted that no one of the researchers studied the impact of inserting a bunch of vertical cooling internals in SBCRs.

**Table 3:** Summary of mass transfer studies on the influence of vertical internals in BCRs-SBCRs

| No. | Author                     | System  | Column dimensions<br>$D_c$ $H_c$ | Range of superficial gas velocities<br>cm/s | Type of tube configurations   | Investigated topic and/or variables                             |
|-----|----------------------------|---|----------------------------------|---|---|---|
| 1   | Chen et al. 1989 [90]      | Air-water/<br>0.2% CMC<br>aqueous<br>solution         | 5, 75, 15 cm<br>3 m              | 0.26–8                                      | 37 circle plates were made using sheets of 6 mesh stainless-steel wire screen.  | The hydrodynamics and mass transfer properties of multistage BC |
| 2   | Kang et al. 1991 [91]      | Air-water/<br>CMC-<br>glass beads                     | 15 cm 2 m                        | Not be defined                              | An acrylic tube with a 15mm diameter that is used as a bubble breaker.  | Volumetric mass transfer coefficient, gas hold up               |
| 3   | Karamanev et al. 1992 [92] | Air-water-<br>glass beads                             | 8, 16, 20 cm<br>1–1.5 m          | Not be defined                              | Draft tubes with $D_i$ (25, 40, 60, 80 and 100 mm).   | Oxygen mass transfer  |
| 4   | Nosier et al. 2004 [93]    | Air-water/<br>$K_2Cr_2O_7$ /<br>$H_2SO_4$<br>solution | 7.9 cm 0.5 m                     | 0.411–<br>4.814                             | 4.7 cm in diameter, 0.3 cm in tube diameter, and 0.84 cm in pitch constitute one copper helical coil. A coil of 17 rings. | Mass transfer rates   |

(Continued)

**Table 3 (continued)**

| No. | Author                      | System   | Column dimensions<br>$D_c$ $H_c$ | Range of superficial gas velocities<br>cm/s | Type of tube configurations   | Investigated topic and/or variables  |
|-----|-----------------------------|--|----------------------------------|---|---|--|
| 5   | Manjrekar et al. 2018 [87]  | Air-water  | 19–45 cm<br>not be defined       | 20–45                                       | 1-Internals in a 19 cm column diameter “1.27 cm diameter robs; 1 pitch” occluded 22% of the CSA;<br>2-Internals in a 45 cm column diameter “2.54 cm diameter robs; 1.75 pitch” occluded 25% of the CSA. | Mass transfer, gas hold up   |
| 6   | Möller et al. 2019 [86]     | Air-water  | 39.2 cm<br>4.2 m                 | 1–22  | Triangular tube configurations in two various “0.045 m square pitch diameter”; “0.032 m diameter” at the identical CSA (25%).   | Mass transfer; liquid mixing and gas phase dynamic   |
| 7   | Al-Shahran et al. 2020 [94] | Air/N <sub>2</sub> -water/<br>K <sub>2</sub> Cr <sub>2</sub> O <sub>7</sub> solution | 12 cm 0.8 m                      | 1.04–2.09                                   | Five horizontal copper pipework arrays are used. Every array is made up of six tubes that are “0.8 cm” in diameter and “12 cm” in length.   | Solid-liquid mass transfer coefficient   |
| 8   | Möller et al. 2020 [89]     | Air-water  | 10–39.2 cm<br>not be defined     | 2–14  | Triangle with four tubes in a square pitch configurations “0.008; 0.013; 0.032; and 0.045” diameter.  | Volumetric mass transfer coefficients; overall gas holdup; sauter mean diameter and interfacial-area |

## 6 Conclusions and Recommendations

The experimental and numerical research findings provide a detailed understanding of the impact of vertical internals; the configurations and diameter of the tube; and the occluded CSA ratio on the hydrodynamic; heat/mass transfer, which are considered to be the most crucial hydrodynamic factors affecting BCR/SBCR efficiency. The effects of inserting heat exchange tubes into BCR/SBCR on flow regime, the intensity of mixing, and overall hydrodynamics are debated. The main conclusions and recommendations for this review are as follows:

1. Bubbles breakage is promoted and smaller bubbles with a tight size distribution are produced by the insertion of vertical tubes for heat exchange, which might significantly enhance gas holdup and interfacial-area while physically reducing turbulence length scales at low superficial velocities.
2. Internals have an effect only if they are present in a significant proportion of the column's CSA. Large-scale liquid circulations are promoted by vertical tubes for heat exchange, while radial dispersion and bubble chord lengths are limiting. The overall gas holdup and HTC improve while the bubble chord-length reduces as the percentage of the column's CSA increases.
3. Compared to the circular configuration of vertical tubes for heat exchange, the hexagonal design considerably enhanced the gas holdup values and distribution of the gases throughout the whole column's CSA.
4. A high percentage of internals enhances the HTC for a given gas velocity, as measured by the flow's free CSA, compared to the column CSA occupied by 0% “empty column”; 5% “simulated methanol-synthesis”; and 22% “simulated FTS”.

5. In relation to the mass transfer investigations, the local turbulence created by particle transitions to the bubble's surface due to the collision characteristic caused a large increase in the mass transfer coefficient on the liquid's side.
6. Future studies should investigate the impact of utilizing finned heat exchange tubes on the heat and mass transfer of BCR-SBCR under high operating conditions.
7. Quantifying the impact of different heat exchange tube diameter on the hydrodynamic and heat/mass transfer of BCR-SBCR using different tube arrangements need to be considered in future studies.

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