

Analysis of Mass Transfer Efficiency in a Compact Wet Scrubber

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This study investigates a compact wet scrubber, a versatile pollution control device designed to efficiently remove particulates and contaminant gases from industrial gas streams. The system features a nozzle integrated into a vertical channel as its core element. The nozzle allows the scrubbing liquid to be injected countercurrently to the descending gas flow. This configuration is intended to create a highly turbulent foam zone, that can significantly enhance mass transfer efficiency. The lack of internal components provides flexibility in handling high-flow gas streams with varying particulate concentrations, making it potentially suitable for a variety of industrial applications. Despite the growing interest in this type of compact scrubber for specific industrial sectors, there is limited knowledge about its design and performance. To address this gap, the present study introduces an experimental setup for characterizing the performance of the compact scrubber. Gas pressure drop measurements across the liquid jet were used as a key tool to identify the scrubber's operating window. Additionally, absorption tests of volatile organic compounds with different solubilities were conducted to assess mass transfer performance. Key parameters, including overall mass transfer coefficient and absorption efficiency, were determined for various gas and liquid flow rates. The results showed remarkable absorption efficiencies of up to 90%, with gas-liquid contact times of less than 1 second.

1. Introduction

Stringent environmental regulations require refineries, cement kilns, power plants, tanneries, chemical manufacturers, and many other industrial facilities to remove pollutants and particulates from flue gases before releasing them into the atmosphere. Meeting the increasingly stringent concentration limits set by these regulations often results in significant energy-related operating costs, driving ongoing efforts to develop more efficient pollution control technologies (EEA, 2024). A wet scrubber is a versatile system that uses a liquid medium to remove particulates and gaseous pollutants from gas streams. Particulates are primarily captured by mechanisms such as inertial impaction, diffusion, and interception, while gaseous pollutants are absorbed into the liquid phase (Danzomo, 2012). Particulate removal is aided by high gas pressure drop and small droplet size, while control of the gas-liquid ratio is critical for pollutant absorption (Park, 2006). Over time, various types of wet scrubbers have been developed to effectively control both particulate and gaseous emissions. These include spray towers, packed or plate towers, ejector or jet scrubbers, cyclone or vortex scrubbers, venturi scrubbers, and others.

When space constraints become critical, not all conventional solutions remain viable. This is particularly true for instance in the marine and offshore sectors, where space is at a premium, necessitating the development of compact scrubber systems (Long, 2025). In these applications, chemical absorption processes with fast reaction kinetics are often preferred (Yao, 2014), reducing the demand for benefits typically associated with conventional packed bed scrubbers (Brunazzi, 2001). For such scenarios, co-current scrubbing emerges as the preferred solution, often implemented with static mixers to ensure efficient operation (Couvert, 2008). However, alternatives to co-current scrubbing are gaining traction, particularly in specialized applications where effective gas-liquid contact is essential, pressure drops must remain low, and gas quenching is necessary. These alternatives are particularly advantageous when gas streams to be treated are loaded with particulate matter, which can lead to clogging in static mixers.

The objective of this study is to optimize the design of an alternative scrubbing system capable of efficiently treating gaseous pollutants and highly dust-laden gas streams. The compact scrubber investigated in this study performs its scrubbing operation by directing the scrubbing liquid countercurrently to the gas flow within the scrubbing chamber, which is designed as an open channel. The gas then reverses the liquid jet, and scrubbing continues in co-current mode. The liquid is sprayed using a full-cone nozzle to ensure complete coverage of the gas passage, preventing potential bypasses. High velocity spraying facilitates effective interaction between the liquid and the gas, promoting efficient mass transfer. This arrangement ensures intimate contact between the two phases, significantly enhancing contaminant removal efficiency. In addition, gas flow through the open channel design minimizes pressure drop and prevents blockage, improving overall system performance. After the contact section, a calming section is incorporated to separate most of the entrained liquid. Before exiting the calming section, the gas passes through a demister that removes any remaining fine liquid droplets. The calming tank often serves as a reservoir for liquid accumulation. A centrifugal pump is typically installed to recirculate the liquid back to the nozzle, ensuring continuous operation.

To optimize the design of the compact scrubber, an experimental setup was designed and constructed. The fluid dynamics were analyzed through visual inspection of the jet during operation and by measuring the gas pressure drop across the liquid jet. Absorption tests with two volatile organic compounds (VOCs) were performed to evaluate mass transfer efficiency. These experimental data are essential for developing comprehensive design criteria that will enable the formulation of correlations and the development or validation of mechanistic models for fluid dynamics and mass transfer in the compact scrubber.

2. Experimental

Figure 1 (left) shows a schematic of the experimental setup. Ambient air enters the system and first passes through the gas-liquid contact section (C) where the scrubbing operation takes place, after the gas enters the separation vessel (D). The liquid is introduced into the contact direction through a solid cone nozzle (N), sprayed upward into the gas flow, which moves in the opposite direction. After reaching a maximum distance from the inlet, the liquid reverses direction and returns to the tank, dragged by the opposing gas stream. The contact section has a diameter of 300 mm and is equipped with three observation windows to allow visual monitoring of the liquid jet dynamics. The airflow is driven by a centrifugal fan, with the gas flow rate measured by a pitot tube and regulated by adjustments to the fan motor inverter. Before exiting the separation tank, the gas stream passes through a chevron-type demister to remove entrained liquid droplets. The liquid is circulated in a closed loop by a centrifugal pump (G), the flow rate is regulated by a control valve and monitored with a flow meter. Figure 1 (right) presents pictures of the experimental setup, showing the separation tank with the liquid reservoir and the contact section with its three observation windows.

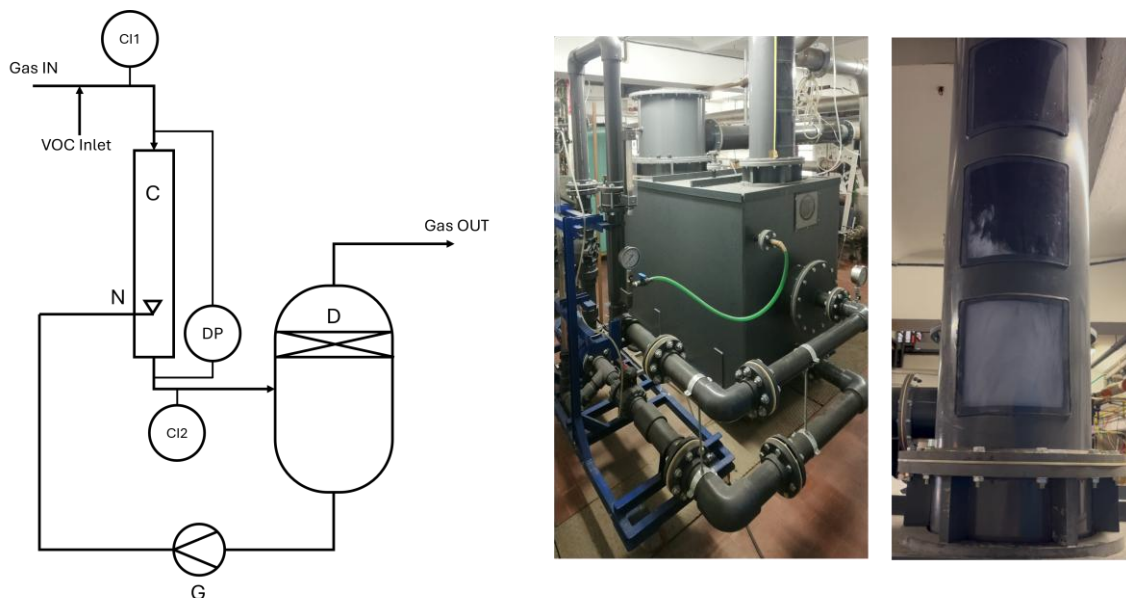


Figure 1: Experimental test rig details (left: schematic of the test rig, right: test rig).

Air-water system was used for fluid dynamic characterization. Gas pressure drops across the liquid jet were measured using a differential pressure transmitter, with sensor ports placed upstream and downstream of the jet.

To evaluate the mass transfer performance of the compact scrubber, absorption tests were performed using two VOCs with distinct water solubilities. Isopropanol (IPA), selected for its high water solubility and low toxicity under the tested conditions, served as the high water-soluble model compound. In contrast, Butyl acetate (BA) was chosen to represent a VOC with poor water solubility, due to its limited solubility in water and its low environmental risk at the concentrations used (Lamprecht and Burger, 2018; Marchini, 2021). VOC concentrations were measured upstream and downstream of the jet using two multi-gas sensors equipped with photon ionization detectors. The VOCs were introduced into the gas line using a diaphragm pump designed to provide a steady and consistent flow into the system. VOC delivery was facilitated by a dual-fluid nozzle that produced a fine mist, ensuring uniform dispersion within the gas stream and promoting efficient vaporization. In the gas stream, VOC concentrations range from a maximum of 600 ppm_v at the inlet to a minimum of 50 ppm_v downstream of the liquid jet. Gas and liquid temperatures were monitored during the experiments.

The experimental setup was designed to provide appropriate liquid-to-gas ratios and gas surface velocities greater than the flooding velocity. Flooding velocity is defined as the minimum gas velocity sufficient to retain liquid flow in an open tube (Roy 1962). The compact scrubber can be considered as an upside-down distillation tray, allowing the flooding velocity to be estimated by considering the total entrainment of the tray (Green, 2008). Based on an estimation of the average droplet diameter, the entrainment (E) can be expressed as follows:

$$E = \left(\frac{u_{s,G}^8 \rho_G^4}{[g(\rho_L - \rho_G)]^{2.5} \sigma^{1.5}} \right) \quad (1)$$

Where $u_{s,G}$ is the gas superficial velocity, ρ_G and ρ_L are the gas and liquid densities, g is the gravitational acceleration and σ is the surface tension. Consequently, flooding conditions occur when the entrainment value is 1. Considering this condition, the value of the flooding velocity is determined (Steinmeyer, 1995).

$$U_{Flood} = \left(\frac{[g(\rho_L - \rho_G)]^{2.5} \sigma^{1.5}}{\rho_G^4} \right)^{\frac{1}{8}} \quad (2)$$

According to the Equation (2), assuming the liquid phase is pure water, and the gas is air, the flooding velocity is estimated to be about 4 m/s. With reference to the diameter of the contact section, the operating flow ranges of the compact scrubber were then determined. Liquid flow rates (L_V) vary between 15 and 45 m³/h, and gas flow rates (G_V) between 500 and 3500 m³/h. For a detailed description of the experimental setup, the reader is referred to Giustacori and Brunazzi 2025.

3. Results and discussion

The VOC concentration in the gas phase is measured across the liquid jet. These measurements allow for the quantification of the instantaneous absorption of the tracer. The liquid is assumed to be homogeneously mixed within the tank, based on the liquid flow rate relative to the tank volume and recirculation loop, as well as the location of the liquid suction point relative to the tank return. Given the selected operating conditions and the short duration of the experiment, the liquid phase can be approximated as a dilute solution. The behavior of the jet, which initially sprays upward before reversing direction to fall back into the tank, along with the intense turbulence, supports the use of a fully mixed model for the liquid in the contact section. In addition, since the gas phase is diluted, VOC transfer within this section is minimal, resulting in negligible changes in both gas and liquid molar flow rates and an almost imperceptible change in liquid temperature. Therefore, the absorption efficiency (E_Y) is determined as follows.

$$E_Y = \frac{y_{IN} - y_{OUT}}{y_{IN} - y_{OUT}^*} \quad (3)$$

Here, y_{IN} represents the molar fraction of VOCs in the gas phase entering the liquid jet zone, while y_{OUT} is the VOC molar fraction in the gas phase after passing through the jet. The term y_{OUT}^* refers to the equilibrium VOC molar fraction in the gas phase, corresponding to the liquid phase composition exiting the jet zone. This formulation accounts for both the actual VOC removal and the theoretical equilibrium limit, providing a measure of the jet's absorption efficiency relative to the maximum possible absorption. Under the assumption of dilute mixture, the VOC water solubility can be described by Henry's law. The Henry constant was calculated considering for the IPA $H_0 = 130$ mol/(kg bar) at 25 °C and a temperature dependence $d(\ln(H))/d(1/T) = 7500$;

instead for the BA $H_0 = 3.6 \text{ mol}/(\text{kg bar})$ at $25 \text{ }^\circ\text{C}$ and a temperature dependence $d(\ln(H))/d(1/T) = 6000$ (NIST, 2024).

Figure 2 (left) shows the trend of absorption efficiency as a function of the F-factor (defined as the product between the gas superficial velocity and the square root of the gas density, $F_F = u_{s,G}\sqrt{\rho_G}$) for various liquid flow rates. As the gas flow rate increases, corresponding to a larger F-factor, the absorption efficiency decreases. A high gas flow rate causes the liquid jet to compress into a region of reduced height, which results in a significant reduction in the contact time between the gas and liquid phases. Varying the liquid flow rate, on the other hand, has different effects. Increased liquid flow enhances jet turbulence, which promotes better mixing and a larger interfacial area for mass transfer. This, combined with increased phase contact time due to the more vigorous jet behavior and the extension of the jet over a larger zone, leads to improved absorption efficiencies. Efficiency trends are similar for both VOCs; however, it is noteworthy that the removal efficiencies of BA are consistently lower than those of IPA under the same liquid flow rate and F-factor conditions.

The gas phase was selected as the reference phase for the mass transfer modeling. The molar flux of VOC transferred between the two phases (N_{VOC}) was modeled as the product of the overall gas side mass transfer coefficient (K_{OY}), contact area (A) and a driving force. Equating this to the molar flux expressed in terms of gas concentration drop across the jet, an analytical expression for the product of the mass transfer coefficient and the interfacial area is derived (Green, 2008).

$$N_{VOC} = G(y_{IN} - y_{OUT}) = K_{OY}A\Delta y_{LM} \quad (4)$$

$$K_{OY}A = G \frac{y_{IN} - y_{OUT}}{\Delta y_{LM}} \quad (5)$$

Where G is the molar gas flow rate and Δy_{LM} the logarithmic mean driving force. Consistent with the absorption efficiency analysis, a completely mixed model is used to describe the liquid in the contact section, and liquid in the tank is considered well mixed.

The trends of $K_{OY}A$ as a function of the F-factor for different liquid flow rates are shown in Figure 2 (right). The results show that $K_{OY}A$ experiences a significant increase with higher liquid flow rates, indicating the degree of increase in absorption surface area in the contact zone. The $K_{OY}A$ values for butyl acetate were significantly lower than those for isopropanol under comparable operating conditions. This result is consistent with expectations and is primarily attributable to the lower water solubility of BA. The lower solubility leads to a decrease in the overall mass transfer coefficient, which includes mass transfer resistances in both the liquid and gas phases. Specifically, the lower solubility of BA in water limits its diffusion and subsequent transfer across phase boundaries.

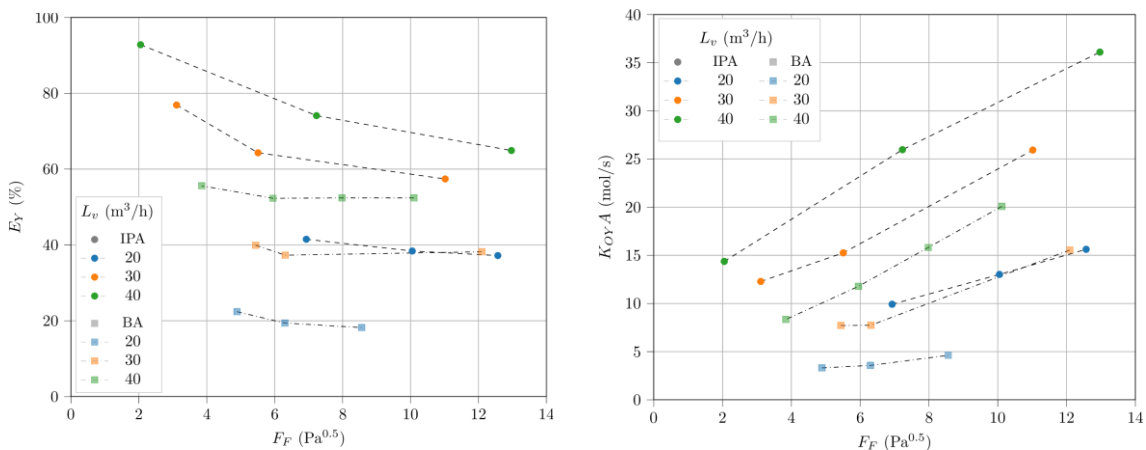


Figure 2: Mass transfer performance results (left: absorption efficiency, right: mass transfer coefficient).

The measurement of the gas pressure drop allowed for the definition of the scrubber operating window; results are shown in Figure 3 (left). Values are shown as a function of the F-factor and for different liquid flow rates. As expected, the pressure drops increase with the liquid flow rate. While for the same value of liquid flow rate, higher F-factors, corresponding to higher gas flow rates result in greater pressure drops. Interestingly, the proposed compact scrubber shows lower pressure drops compared to static mixer solutions commonly used in industrial applications (Couvert, 2008). The major contribution to pressure drop is from the liquid jet. However,

given the limited size of the contact zone, the pressure drops are limited. This difference is mainly due to the main feature of the scrubber, since there is no impeding to the gas flow except crossing the liquid jet.

During pressure drop tests, it was found that for high liquid flow rates and reduced gas flow rates, the system enters a pulsed operating mode. In this regime the liquid tends to accumulate at the top of the jet and, when critical condition is reached, the liquid piston is discharged. This condition happens cyclically and can cause mechanical problems.

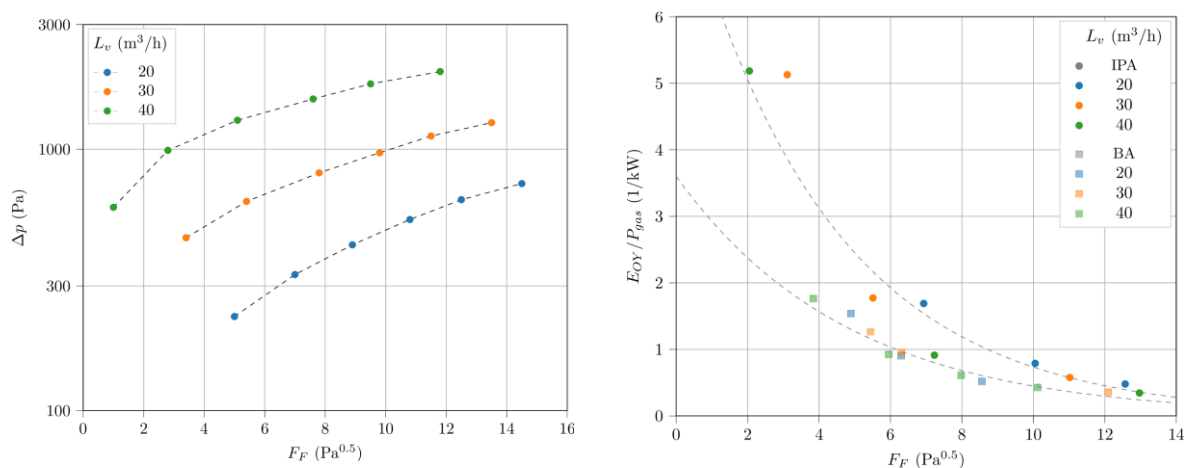


Figure 3: Pressure drops test results (left: pressure drops, right: ratio between absorption efficiency and gas power loss)

The power dissipated by the gas in passing through the liquid jet can be expressed as the product between the gas volumetric flow rate and the pressure drop experienced by the gas passing through the liquid jet (Δp).

$$P_{gas} = G_V \cdot \Delta p \quad (6)$$

As expressed in equation (6), the power dissipated in the system is directly proportional to the gas flow rate and the pressure drop, which in turn is affected by both the gas and liquid flow rates. Figure 3 (right) illustrates the relationship between scrubbing efficiency per unit of power and the F-factor. Notably, the data for both test systems converge on a single curve under all experimental conditions. This convergence demonstrates that the absorption efficiency per unit power has a consistent proportional dependence on the gas flow rate, regardless of the specific system configuration or test conditions. This observation suggests a fundamental principle governing scrubber operation, with significant implications for design optimization. By integrating this trend with additional data on pressure drop and operating gas flow rates, a more complete understanding of scrubber performance can be achieved. This insight facilitates the development of advanced design and operation strategies aimed at maximizing the efficiency of compact scrubbers for enhanced removal of gaseous pollutants.

4. Conclusions

This study investigates a compact scrubber with the goal of establishing optimized design criteria for this technology, focusing on pollutant removal performance. In order to define the operating ranges of the equipment and to improve the mass transfer efficiency, an experimental setup was designed and constructed. Fluid dynamic characterization was performed by measuring the gas pressure drop across the liquid jet and by visual inspection of the jet. The experimental results showed that the pressure drops increased with higher gas and liquid flow rates. Pulsation in the system was observed when the scrubber was operated at high liquid flow rates and low gas flow rates, which was attributed to cyclic jet behavior. Mass transfer tests were conducted using two different test systems to evaluate the absorption efficiencies. The experiments demonstrated high absorption efficiencies, with values up to 90% for highly soluble VOCs. The mass transfer within the jet was modeled, and the total mass transfer coefficients of the compact scrubber were determined. The results showed that the product of the total mass transfer coefficient and the interfacial area ($K_{OY}A$) increased with liquid and gas flow rates.

This study highlights critical relationships that govern the performance of compact scrubbers. As shown by the data in Figure 3, the absorption efficiency per unit power exhibits a consistent proportional dependence on gas flow rate, regardless of system configuration or test conditions. This trend underscores a fundamental principle of scrubber operation with significant implications for design optimization. The critical role of gas pressure drops

across the liquid jet in influencing scrubbing efficiency further emphasizes the importance of optimizing the relationship between absorption efficiency per unit power and volumetric gas flow. These findings not only provide a basis for mass transfer characterization, but also lead the way to the development of advanced design strategies. By integrating the observed trends with further studies of mass transfer mechanisms, compact scrubbers can be better designed to maximize pollutant removal while minimizing energy consumption. This has direct implications for industrial applications, where enhanced scrubber efficiency can lead to lower operational costs, reduced environmental impact, and improved compliance with air quality regulations. Future research could focus on refining design parameters and exploring alternative liquid-gas configurations to further enhance performance and adaptability in diverse industrial settings.

Nomenclature

A – interfacial area, m^2	P_{gas} – gas power dissipation, kW
E – entrainment, -	$u_{s,G}$ – gas superficial velocity, m/s
E_Y – absorption efficiency, -	U_{Flood} – flooding velocity, m/s
F_F – F-factor, $Pa^{0.5}$	y_{IN} – gas inlet molar fraction, -
g – gravity acceleration, m/s^2	y_{OUT} – gas outlet molar fraction, -
G – gas molar flowrate, $kmol/s$	y_{OUT}^* – gas outlet equilibrium molar fraction, -
G_V – gas volumetric flowrate, m^3/s	Δp – gas pressure drops, Pa
H – Henry constant, $mol/(kg \text{ bar})$	Δy_{LM} – logarithmic mean driving force, -
K_{OY} – overall mass transfer coefficient, $kmol/m^2s$	ρ_G – gas density, kg/m^3
L_V – gas volumetric flowrate, m^3/s	ρ_L – liquid density, kg/m^3
N_{VOC} – molar flux, $kmol/s$	σ – surface tension, N/m

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