

# Effects of process conditions on foaming in stirred tanks

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**Abstract:** The effect of impeller speed and type, as well as gas flow rate on the amount of foam generated in a 5L stirred tank has been studied. Foam height was found to increase with increasing impeller speed after a critical impeller speed was reached. It also increased with increasing gas flow rate. The disc turbine creates significantly more foam than the down-pumping hydrofoil for a given tip speed. Scale-up guidance to correctly replicate the amount of foaming in larger scale tank was also investigated. It was found that impeller tip speed was the best scale-up invariant, compared with power per unit volume and the Weber and Froude numbers. It is less clear, however, which is the best scale-up invariant for the gas flow rate; aeration number appears more adapted than the superficial gas velocity or the ratio of gas flow rate to liquid volume, however it does not always correctly replicate the gas-liquid flow regime.

**Keywords:** stirred tank, gas-liquid, foaming, scale-up

## Introduction

Foaming is observed in a range of chemical industries such as textile and paper manufacturing, fine chemical, agrochemical and pharmaceutical production, and the food industry. For some processes the foam formation is desired and even important for the product (e.g. beer and cleaning products) [1]. For other processes, foaming is undesirable and can have negative impact on the production. Excessive foam formation in chemical reactions typically leads to higher than expected volumes inside the reactor with parts of the headspace taken up by foam. To ensure that the reactor is not overflowing, the fill level must be reduced thus decreasing the batch size and overall productivity.

Foaming is often observed for gas-liquid systems, for example when gas is generated during a reaction, when gas is sparged into a reactor or when gas entrainment from the headspace occurs. A well-known solution to reduce foaming is to use antifoams or defoamers. However, the use of antifoams introduces new chemicals to the system and significant work to assess the impact of the addition and the need for potential re-registration of products might be required. Additionally, the use of antifoams can increase the production cost making it a less attractive solution. An interesting alternative to foam mitigation could be to use non-chemical solutions such as modifications to the operating conditions or the equipment.

Whilst there are a number of papers in the literature that report on foaming in stirred tanks, most of these focus on the design and performance of foam breakers, which are employed to destroy foam that has been generated by the aerated stirred tank itself. These are typically impellers, discs or cones rotating close to the liquid surface that are used in addition to a tradition impeller system for mixing purposes [2-9]. Although these studies have shown that the geometry, size, position and rotational speed of the foam breaking device, the gas flow rate and the physical properties of the gas-liquid system affect foam destruction [3,4,10-12], there is a lack of systematic information on how the operating conditions and the geometry of a stirred tank itself affect foam generation. Moreover, only limited work on scale-up/scale-down of foaming in stirred tanks has been carried out [8,15]; as a result, there is very little guidance for replicating and controlling foaming behaviour of gas-liquid stirred tanks across scales.

The aim of this work is to investigate the effects of the gas-liquid stirred tank process conditions, e.g. impeller type and speed, gas flow rate, on foam generation and to develop scale-up / scale-down guidance for replicating foaming behaviour across scales. To do this, experiments have been performed at two scales (5L and 170L) using two impeller types (a disc turbine and a hydrofoil).

## Material & methods

### Experimental set-up

Two transparent dished-bottom cylindrical tanks with  $T_1 = 0.19$  m and  $T_2 = 0.6$  m and volumes of 5L and 171L, respectively, were used for the experiments. Each tank was equipped with four baffles with width  $w_b = T/8$  and the initial liquid height,  $H$ , was equal to the tank diameter. A ring gas sparger with diameter  $T/3$  was placed below the impeller and used to introduce air into the tank. Two impeller types were used: a 6-bladed disc turbine ( $D = T/3$ ) and a narrow-bladed 3-blade hydrofoil ( $D = T/2$ ). The impeller off-bottom clearance was  $C = T/3$ . Torque was measured with an integrated torque meter in the Lighnin Labmaster motor for the small tank and with a Hottinger Baldwin Messtechnik torque meter installed on the shaft of the large tank. The air flow rate was measured using Sho-Ratë rotameters with ranges of 0.116 – 17.4 Standard Liters Per Minute (SLPM) and 0.287 – 43.0 SLPM for the small and large tanks, respectively.

### Fluids

The liquid used in this study was an aqueous solution of Tween® 20 (ARCOS Organics) with a concentration of 0.1 g/L. This concentration is higher than the critical micelle concentration (CMC) of 60 mg/L which ensures that the liquid surface tension is constant. The density of the solution is 997 kg/m<sup>3</sup> and the surface tension is 67.0 mN/m at 18°C, which was the operating temperature. The gas phase is air.

### Operating conditions

In the small tank, the impeller speed was varied in the range 200 to 550 rpm, which corresponds to turbulent flow and impeller tip speeds in the range 0.7–2.0 m/s for the disc turbine and 1.0–2.9 m/s for the hydrofoil. The gas flow rate was varied between 1.16 SLPM and 6.96 SLPM. In the large tank, the impeller speed was in the range 67–183 rpm, which also corresponds to turbulent flow and the same range of impeller tip speeds as in the small tank. The gas flow rate was varied between 3.5 SLPM and 18.1 SLPM.

### Measurement method

For each experiment, the impeller and gas flow were turned on and the foam height was measured after 10 minutes. The gas-liquid dispersion regime (flooded, loaded or dispersed), the torque value and a short description of the foam was also recorded. Between each experiment, the foam was destroyed completely by blowing air onto it from outside the tank. Prior to each test, the tank walls were wetted to provide the same wall surface condition for the foam. The tank solution was changed after 4 hours of use.

The foam height was measured over the radius of the tank at four positions (midway between two baffles) using measuring tapes that were fixed to the outer tank wall. The four values were then averaged to provide a single foam height value,  $h$ , for each experiment. Since the foam height was not uniform across the cross-section of the tank, the recorded foam heights were considered to be the highest points reached by the foam over the radius of the tank at each of the four positions. The highest point of the foam was chosen because it is relatively easy to identify and also because the maximal foam height is an important parameter during the operation of industrial reactors. In order to be able to compare the foam heights across scales, the dimensionless foam height was calculated as:

$$h^* = \frac{h}{H} \quad (1)$$

## Results and discussion

### Effect of operating conditions on foam generation

Typically, three different types of foam were obtained depending on the impeller speed, gas flow rate and impeller type, as shown in Figure 1. Foam type A occurs for low impeller speeds and gas flow rates, and consists of relatively large bubbles. As a result, the foam is not dense and tends to disappear quickly after gassing and mixing is stopped. At intermediate impeller speeds and gas flow rates, foam type B is formed. It is comprised of a combination of average-sized bubbles and smaller bubbles, making the foam more dense and stable than foam type A. Foam type C is created at high impeller speeds and gas flow rates and is comprised of small bubbles that create dense foam, which

sticks to the tank wall, and is stable for a few hours if left undisturbed. Foam type C is created more often with the disc turbine than the hydrofoil in the range of impeller speeds tested.

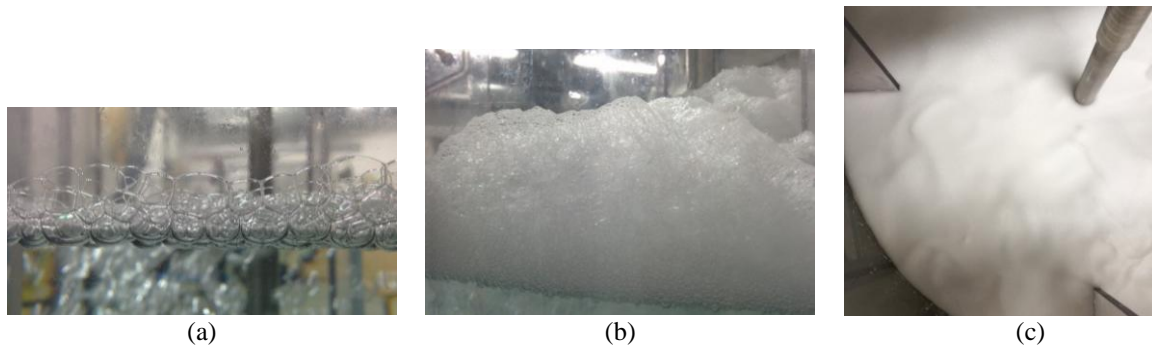


Figure 1: Different foam types obtained in the stirred tank (a) Foam type A; (b) Foam type B; (c) Foam type C.

Figure 2(a) shows the dimensionless foam height in the 5L tank as a function of impeller tip speed for different gas flow rates and the two different impeller types. The error bars correspond to the standard error of the measured foam height. In a general manner for both impeller types, it can be seen that the foam height is low and more or less constant at low tip speeds and then increases sharply at a certain critical tip speed. This critical tip speed appears to be dependent on both the impeller type and gas flow rate. The critical tip speed is much lower for the disc turbine than for the hydrofoil; as a result, the disc turbine produces much more foam than the hydrofoil at an equivalent tip speed and gas flow rate. This may be explained by the higher power dissipation and shear rates created by the disc turbine that are responsible for bubble breakup. It can also be seen that for a given impeller tip speed, foam height increases with increasing gas flow rate, which is logical since increased gas flow rate gives rise to an increased gas hold up. Indeed, the effect of the gas flow rate on foam height is more noticeable for the hydrofoil. For the disc turbine, there is little effect on the foam height when intermediate and high gas flow rates are used and it appears that the impeller is the controlling parameter.

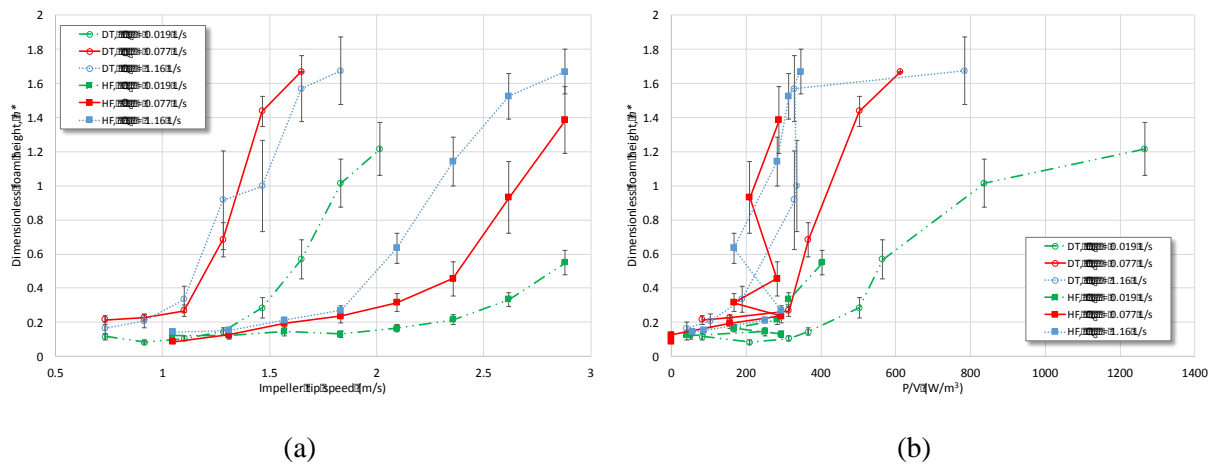


Figure 2: Foam height as a function of (a) impeller tip speed and (b) power per unit volume for different impellers and gas flow rates.

Figure 2(b) shows the dimensionless foam height as a function of power per unit volume for the two impeller types and different flow rates. Although there is not a neat trend, it does appear that the foam height data does correlate to some extent with the power per unit volume, at least for the intermediate and high gas flow rates.

### Scale-up strategies

As seen from the previous results, foam generation is controlled by impeller type and speed, as well as gas flow rate. This suggests that both a parameter relative to the impeller and to the gas flow rate need to be kept constant for scale-up, in addition to the similarity of geometry at both scales.

Concerning gas flow rate, three parameters were explored: superficial gas velocity, the ratio of gas flow rate to liquid volume  $Q_G/V$ , and the aeration number,  $Na = Q_G/ND^3$ . For a constant impeller tip speed of intermediate value, it was found that the dimensionless foam heights in the 171L tank are most similar to those in the 5L tank when the gas flow rate is scaled-up using  $Na$ . However, at higher impeller speeds, none of the scale-up methods correctly reproduce the dimensionless foam height at both scales. Indeed, very often the dispersion regime is not correctly reproduced. Nevertheless, constant  $Na$  was used at both scales to explore the scale-up parameter for impeller speed/type because this best replicated foam generation at intermediate impeller speeds.

Four invariants for scaling-up impeller speed were explored, namely  $P/V$ , Weber number, Froude number and impeller tip speed. Scaling-up with  $P/V$  constant lead to a very high impeller rotational speed and extremely high dimensionless foam heights in the 171L tank, except when the dispersion regime was flooded in the 5L tank. Furthermore, the bubbles were always well dispersed in the large tank, even when the flow regime was not completely dispersed in the small tank. Scaling-up with constant Weber number resulted in impeller speeds that were far too low compared with the small scale, making it impossible to obtain complete dispersion like that achieved in the small tank. On the other hand, when the Froude number was used, impeller speed and gas flow rate were much too high compared with the small scale, thereby creating a very large amount of foam. Scaling-up using constant impeller tip speed gave the most promising results, as shown in Figure 3.

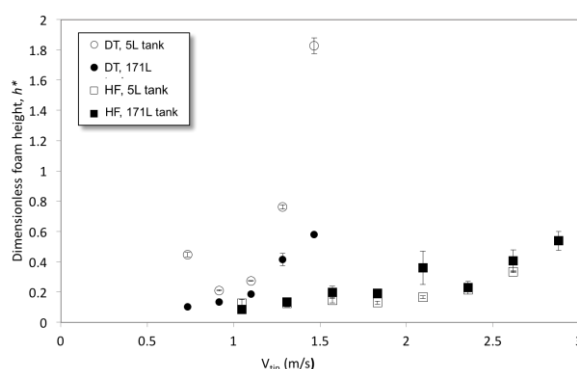


Figure 3: Scale-up of foam height using constant impeller tip speed and aeration number.

## Conclusions

The effect of impeller type and speed, as well as gas flow rate on foaming have been studied at two different scales. The hydrofoil impeller generated significantly less foam than the disc turbine at similar impeller tip speed and gas flow rate. This was ascribed to the lower shear rates and energy dissipation created by the hydrofoil, thus resulting in a foam with bigger bubble size, which was less stable and less dense. It was found that the impeller speed has a more significant impact on the amount of foam created than the gas flow rate. Results also showed that impeller tip speed is the best parameter to be kept constant to mimic foaming behavior across-scales. This may be due to the fact that shear stress, which breaks bubbles, depends on the impeller tip speed. Three strategies for scaling-up the gas flow rate were tested, namely gas superficial velocity,  $Q_G/V$ , and aeration number. However, the best strategy for scaling up the gas flow rate has not been determined since all three methods gave unsatisfactory results in reproducing the dispersion regime observed in the small scale. Nevertheless, the aeration number gave the closest results for both the large and small scale tanks.

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