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Effect of gas flow on the bending moment acting on a shaft in a sparged vessel stirred by a Pitched Blade Turbine

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A B S T R A C T

The bending moment acting on the overhung shaft of a gas-sparged vessel stirred by a Pitched Blade Turbine, as one of the results of Fluid–Structure Interactions (FSI) in stirred vessels, was measured using a moment sensor equipped with digital telemetry. The amplitude and Power Spectral Density of the shaft bending moment were analyzed. It shows that the gas flow has a considerable influence on the characteristics of the bending moment, such as the amplitude mean, distribution, Standard Deviation and peak, and the low-frequency and speed frequency contributions to the fluctuation. The relative mean bending moment initially increases with gas rate till the transition from complete dispersion to loading regimes, approaching a peak, then decreases to a valley and again rises gradually, going through the transition from loading to flooding regimes. The "S" trend of the relative mean bending moment over gas flow rate, depending on the flow regime in gas–liquid stirred vessels, results from the competition among the nonuniformity of bubbly flow around the impeller, the formation of gas cavities behind the blades and the gas direct impact on the impeller as gas is introduced.

Keywords: Bending moment; Gas–liquid flow; Gas sparged stirred vessel; Fluid–structure interaction

1. Introduction

Impeller stirred vessels play an important role in many chemical processes, enhancing chemical transport through the input of mechanical energy into the fluid. Such vessels generally contain baffles, coils or other internals designed to enhance the mixing, heat transfer or other desired process results. Thus, for a typical well balanced impeller system where the center of gravity of the impeller and shaft is perfectly aligned with the axis of rotation and this in turn is perfectly aligned with the vessel centerline, the fluid motion produced by the impeller is not, in general, symmetric in the spatial structures including primary circulation loops, liquid swell on free liquid surface (Bruha et al., 2011) and trailing vortices behind the impeller blades (Escudie et al., 2004). The flow in such systems is also unsteady due to low-frequency macro-instabilities (Hasal et al., 2004; Montes et al., 1997; Roussinova and Kresta, 2004), blade passing frequency pseudo-turbulence (Vantriet et al., 1976) and high-frequency turbulent motions (Liu et al., 2008). These asymmetric, unsteady fluid motions exert an imbalanced and unsteady load (Kratena et al., 2001; Weetman and Gigas, 2002) on the impeller and lead to instantaneous deflections of the shaft and impeller. The resulting lateral movements of the impeller and shaft in turn induce further unstable and nonuniform flows around the impeller. In fact, this behavior in stirred vessels is an example of the bidirectional interactions of a flowing fluid with a flexible structure (Dowell and Hall, 2001). Various features of the flow in stirred vessels can further intensify the effects of FSI, such as instabilities in the liquid free surface

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Nomenclature

C	clearance of impeller off bottom of vessel (m)
d	diameter of shaft (m)
D	diameter of impeller (m)
D_s	diameter of sparger (m)
f_n	the first order laterally natural frequency (s^{-1})
f_r	the first order laterally resonant frequency (s^{-1})
Fl_G	gas flow number of impeller
Fr	Froude number of impeller
H	height of liquid free surface in stirred vessel (m)
L	overhung length of the overhung shaft (m)
m_{imp}	mass of impeller (kg)
m_u	part unbalanced mass of impeller (kg)
M_b	bending moment acting on the overhung shaft (N m)
M_c	combined moment acting on the overhung shaft (N m)
M_t	torque acting on the overhung shaft (N m)
n	operational speed (rot min^{-1})
N	operational speed frequency (rot s^{-1})
PSD	Power Spectral Density ($N^2 m^2 s$)
Q_G	gas flow rate ($m^3 h^{-1}$)
r_u	distance of part unbalanced mass off geometrical center (m)
S	sparger height off bottom of vessel (m)
S_S	sampling scale (sampling number)
SP	spectral power ($N^2 m^2$)
T	diameter of vessel (m)
U_b	unbalance of impeller (g mm)
W_b	width of baffle (m)
x	Weilbull random variable

Greek letters

μ	Mean (N m)
σ	Standard Deviation (N m)
β	shaft bending moment coefficient
σ^2	Variance ($N^2 m^2$)
λ	scale parameter of Weibull distribution (N m)
κ	shape parameter of Weibull distribution
δ	distance between centers of gravity and geometry (m)
Γ	Gamma function

Subscripts

G	gas
L	liquid
b	bending
t	torsion

superscript

—	time-averaged

or the non-uniformities associated with multiphase flow, as can mechanical design features such as any imbalance of the shaft and impeller combination caused by manufacturing tolerances and the natural frequency of stirring structures in the lateral direction.

In stirred vessel operation, the function of the shaft is to transmit power from the drive train to the impeller and the resulting torque must be borne by the shaft. Meanwhile, an unsteady bending moment is also exerted on the shaft due to the lateral deflection of the shaft and movement of the impeller produced by the complex FSI in the stirred vessel. This results in a dynamic load on the stirred vessel head supporting the shaft. In the mechanical design of mixing equipment, the underestimation of the shaft bending moment leads to plastic deformation and fatigue failure of shafts and vessels. However, it is difficult to theoretically determine the bending moment because of the complex nature of the fluid dynamics, the nonlinear structural dynamics and the coupling dynamics of the FSI in stirred tanks.

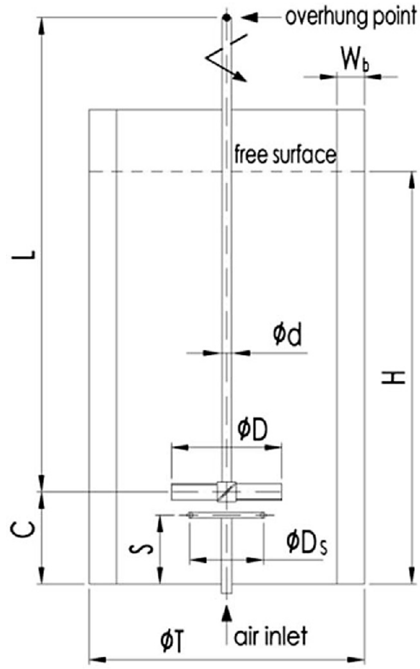

Fig. 1 – Sketch of the laboratory scale vessel used in the experiment.

When gas is sparged into stirred vessels, the 2-phase nature of flow can increase both asymmetries and unsteadiness in the flow field compared with the single phase situation, which further increases the shaft bending moment by virtue of intensifying the FSI. To date, little research on the lateral loads acting on gas sparged stirred vessels has been published still. In this paper, we report an experimental study examining the impact of gas flow on the shaft bending moment in a Pitched Blade Turbine stirred vessel. The main purpose is to provide quantitative data on the magnitude of the loads on gas–liquid stirred vessels for the mechanical design of these systems.

The results derived from this study include the mean, Standard Deviation and peak of the shaft bending moment for different gas rates covering complete dispersion, loading and flooding regimes in sparged stirred tanks. These are respectively applied to the tensile strength check, fatigue failure analysis and yield strength check in the mechanical design. Moreover, the bending-torsion combined moment as a function of gas flow number is also presented.

2. Model and method

2.1. *Experimental model*

The laboratory scale vessel used in the experiment is shown in Fig. 1 and the key details are given in Table 1. Geometrical details of the modified PBT are shown in Fig. 2.