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Pumping capacity of inline dynamic mixers and its effect on process flow control

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ABSTRACT

A semi-empirical (dimensional) model has been developed to predict the performance of an inline dynamic mixer within a specific application to ensure effective process design and operation. Inline dynamic mixers (or rotor-stator mixers) are known to behave like centrifugal pumps, particularly when operating at high rotor speeds. A mismatch between the process flowrate and the mixer's inherent pumping action can result in either high or low pressure at the inlet of the rotor-stator mixer, which can influence process control. Experiments were conducted at pilot scale using three models of inline dynamic mixers from Silverson Machines Ltd., with water as the process fluid. A wide range of flowrates and rotor speeds were covered where the pressures at the inlet and outlet of the Silverson were measured in each condition. A good correlation ($R^2 = 0.9998$) between Silverson inlet pressure, process flowrate and rotor tip speed has been established but the expression requires knowledge of the nominal flowrate of the mixer model at a benchmark rotor tip speed. This reported model can serve as design criteria when selecting mixer models even at production scale.

1. Introduction

The ability to predict equipment performance using mathematical models within a specific application is one of the key enablers to effective process design and operation. It can smoothly facilitate the selection of the appropriate equipment design, not only based on its individual specification but also in terms of its compatibility with the operating conditions of the entire process. Developing this capability can aid process innovation, which then accelerates product development and improves supply chain efficiency (Pisano and Wheelwright, 1995).

Towler and Sinnot (2013) describe the design process as an iterative procedure. As the design develops, more possibilities and constraints arise which will constantly require new data to evaluate possible design solutions. When equipment design alternatives are suggested, they must be tested for fitness for purpose. However, building several designs to find out which one works best is both cost and resource-intensive (Cohen, 2005). Therefore, in most cases, experienced engineers usually rely on tried and tested methods and use previous designs for similar products and processes. The better approach, however, to build a mathematical model of the equipment and predict its performance in possible process applications.

A good example which will benefit from this performance model is the operation of an inline dynamic mixer as part of a manufacturing process. Inline dynamic mixers (or rotor-stator mixers) are widely used in a variety of industries, spanning food (Hanselmann and Windhab, 1998), cosmetics (Choplin et al., 1998), chemical (Jasinska et al., 2013), and pharmaceuticals (Khan et al., 2011), to provide the high shear mixing duties such as homogenisation, emulsification and dispersion (Atiemo-Obeng and Calabrese, 2004). Like centrifugal pumps, they can generate a significant pumping action, which in some situations, is sufficient to transport liquids whilst simultaneously emulsifying and/or dispersing material (Sparks, 1996). Due to their widespread use, several studies reported on how to accurately describe their power draw characteristics (Bourne and Studer, 1992; Kowalski et al., 2010) and the hydrodynamics inside the mixing head (Barailler et al., 2006; Utomo et al., 2008). Ozcan-Taskin et al. (2011) investigated power and flow characteristics of rotor stator geometries and how they could affect pumping capacity.

Atiemo-Obeng and Calabrese suggested that although rotor-stator mixers can pump to some extent (which Silverson mixers are a good

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Nomenclature

D	Rotor diameter, m
F_{10}	Flow ratio, $\frac{Q}{Q_{Nom,10}}$
N_Q	Pumping number, an equipment coefficient depending on the precise geometry
k_A	Term to account for flowrate effect, bar
k_B	Term to account for tip speed effect, (bar s^2)/m^2
N	Rotor speed, rpm
P_1	Silverson inlet pressure, bar
P_2	Silverson outlet pressure, bar
P_{adj}	Adjusted pressure term used to normalise data at $S = 10$ m/s, bar
Q	Process flowrate, kg/min
Q_{Nom}	Silverson nominal flowrate where $P_1 = 0$, kg/min
$Q_{Nom,10}$	Silverson nominal flowrate where $P_1 = 0$ and $S = 10$ m/s, kg/min
S	Rotor tip speed, m/s

example), an external feed pump is preferred to control the flowrate into the mixer. Manufacturers will strongly advice to ensure that the unit is not ‘run dry’ which can lead to equipment damage. The pump ideally dictates the main process flowrate and therefore the residence time of the liquid in the mixer. The rotor speed is then varied to control the energy input and shear rates into the liquid. When there is negligible pressure drop across the rotor-stator mixer, the flowrate generated by the mixer is almost equal to the process flowrate. This is of course not true when the inline dynamic mixer is over-sized for the application. For precise flow control of feed rates which is vital when streams are being metered continuously at a desired stoichiometry, this is the ideal situation. However, a possible mismatch between these two flowrates can be expected when operating a pump and a rotor-stator mixer independently in the same process line. Unfortunately, further literature search revealed limited predictive engineering knowledge on how the inherent pumping action of rotor stators can affect process flow control.

The objective of this paper is to report a semi-empirical model based on a pressure and flowrate correlation for predicting effects due to pump and inline dynamic mixer flow mismatch. Trials were conducted to collect data from three pilot scale models of inline dynamic mixers from Silverson Machines Ltd (Section 2). Results were reported and analysed, taking a step-by-step approach in accounting for scale, tip speed and flowrate effects and later using a statistical software to combine all these effects (Section 3). The final expression will be useful in two aspects: first, aiding in the selection of inline dynamic mixers by providing a key design criteria for a specific process application, and second, ensuring smooth process flow control during operation.

2. Experimental facilities and methods

2.1. *Silverson inline dynamic mixers*

Three double screen pilot-scale models, Silverson 88/150 Verso, 150/250 MS and 275/400 MS, were used in this study.

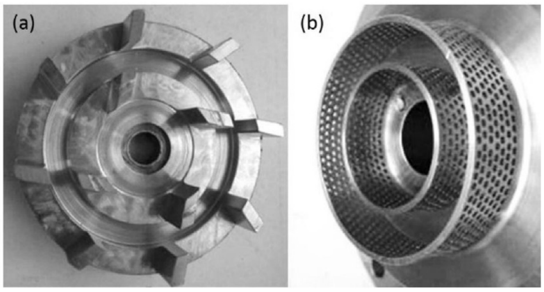

Fig. 1 – (a) Double concentric rotor and (b) matching emulsor screens of a Silverson 150/250MS.

Each model has a double concentric rotor (Fig. 1a) which sits within close fitting screens (Fig. 1b). The two numbers that describe the model refer to the diameter of the inner and outer rotors; for example, Silverson 88/150 has a nominal inner rotor diameter of 0.88 in. and a nominal outer rotor diameter of 1.5 in. The screens used were the emulsor screens supplied as standard with the units. The outer rotor diameter D was used for tip speed calculations [Eq. (1)].

$$S = \pi N D \tag{1}$$

where S is the rotor tip speed (m/s), N is the rotor rotational speed (rps), D is the outer rotor diameter (m).

The Silverson pumping capacity is defined by the linear relationship of the rotor diameter D (m) and speed N (rpm) (Streeter and Wylie, 1983). This is proportional to the flowrate generated by the rotor stator mixer at which there is no pressure drop over the machine [Eq. (2)]. In this paper, this was called as the nominal flowrate Q_{Nom}.

$$Q_{Nom} \propto N \cdot D^3 \tag{2}$$

where Q_{Nom} is the Silverson nominal flowrate (kg/min). Silverson Machines Ltd. has provided the nominal flowrates for a range of models at a nominal rotor speed (Table 1). This information is typically used as a criterion on machine selection but is not sufficient to cover variable rotor speeds and process flowrates.

2.2. *Experimental design*

The study was designed to explore variable pump and Silverson rotor speeds to determine flow mismatch effects. The experiments were conducted at pilot-scale using the arrangement shown in Fig. 2. Water (demineralised and chlorinated) at ambient temperature was added to a 200 L stainless steel jacketed vessel (open tank) and pumped around the loop by a Microbeclean sanitary lobe pump (APV) at various speeds from 10 to 90% pump speed at intervals of 10. One Silverson model was installed at a time and was operated at selected rotor speeds to generate tip speeds of 5, 10, and 20 m/s [Eq. (1)]

Table 1 – Nominal flowrates of Silverson machines and their calculated pumping capacity.

DS Silverson model	Outer rotor diameter, D (mm)	Nominal rotor speed, N (rpm)	Nominal flowrate, Q_{Nom} (kg/min)
88/150	38.1	6000	(Not supplied)
150/250	63.3	3000	75
275/400	101.5	3000	167
312/450	114.3	2850	367
450/600	152.4	2850	867
500/700	177.8	2850	1250

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