Perspective

Challenges in Mitigating Lubricant Foaming

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Abstract: Lubricant foaming and its mitigation is an active area of research driven by demands from modern machinery that require foam-free lubricant operation over extended periods and under adverse conditions. Tackling lubricant foaming has proven to be challenging due to interdependent foam stabilization mechanisms and a multitude of antifoam inactivation routes. This perspective briefly outlines the key challenges faced by researchers in this field. Overcoming these challenges to create lubricants with superior foaming characteristics requires the development of new lubricant and antifoam chemistry as well as a shift from the existing trial-and-error methods to mechanistic-insight-driven lubricant formulation and antifoam design.

Keywords: viscosity; particulates; surfactants; solutocapillary; thermocapillary; interfacial rheology; antifoam filtration; antifoam degradation; antifoam inversion; antifoam settlement

1. Introduction

Lubricant foams are dispersions of gas bubbles in a liquid lubricant [1]. They are commonly generated during the operation of lubricated machinery, often via the natural entrapment of air accompanying lubrication modes, such as splash lubrication or via the release of dissolved gases in the lubricant due to changes in the pressure and temperature [2]. Lubricant foams are undesirable as they are known to increase wear in lubricated machinery, increase overheating in machinery due to reduced lubricant thermal conductivity, increase energy losses and reduce lubricant life through increased oxidation [3].

The focus on mitigating lubricant foaming was limited in the past due to frequent machinery servicing and expected low machinery lifespans. However, in recent years, there has been a renewed interest in systematically understanding lubricant foaming, mostly driven by the advent of high-performance modern machinery. A pertinent example is the wind turbine, which is expected to operate unattended for extended periods under extreme conditions.

In the absence of frequent and costly servicing, foaming and foam-related degradation of lubricants can lead to structural failures within the gearbox [4]. This has prompted leading Original Equipment Manufacturers (OEMs), technical societies and major lubricant manufacturers to call for 'foam and air release' to be a key lubricant formulation parameter for wind turbine lubricants [5,6].

Formulating lubricants with ideal foaming and air release characteristics has proven to challenging. This is unsurprising given a multitude of interdependent foam stabilization mechanisms and antifoam inactivation routes. A brief overview of the challenges faced by researchers in this active research area is given below.

2. Eliminating Profoamers

A straightforward way of improving foaming performance is to eliminate profoamers and associated mechanisms. Commonly recognized profoamers include viscosity, particulates, surfactants, solutocapillary effects, thermocapillary effects and interfacial rheology [7]. Viscosity retards foam drainage and enhances foam stability [1,8]. Changes to

lubricant viscosity to mitigate foaming are often constrained by machinery type and the operating conditions.

When such changes are possible, the viscosity is tuned by blending lubricant oils. Unfortunately, lubricant blending leads to an increase in the lubricant compositional heterogeneity, often promoting phase-separation-mediated [9] and solutocapillary-mediated foam stabilization [10]. Particulates, commonly introduced via external contamination or from the natural wear of machinery, can promote Pickering-type foam stabilization [11,12]. Filtration is the simplest method for removing particulate content. Unfortunately lubricant filtration can promote foaming in fully formulated lubricants due the unintended removal of antifoam additives (see next section).

A number of lubricant additives, such as anti-wear agents, friction modifiers and corrosion inhibitors, are surface active. Such additives are known to become effective surfactants and promote foaming close to their phase-separation boundary [1,8,13]. Changes to additive concentrations are often constrained by the additive type [14–17], their intended application [1] and their interdependence on additive stability (including that of antifoams) [18], which makes them a difficult target for foam mitigation.

Solutocapillary and thermocapillary foam stabilization are brought about by Marangoni flows originating from spatial gradients in species concentration [19] and temperature [20], respectively. As previously mentioned, solutocapillary foam stabilization is prevalent in lubricants with compositional heterogeneity, which includes most lubricant base oils refined from crude oils [10]. Synthetic lubricant oils with a homogeneous composition are devoid of solutocapillary effects and are increasingly forming the basis for the next generation of lubricants [21].

The notable downside of synthetic lubricants is their high cost. Even with synthetic lubes, completely eliminating solutocapillary effects can become challenging due to the need to blend stocks for controlling the bulk properties, such as viscosity. Thermocapillary effects are even harder to control as they are inherently dependent on the temperature fields generated during machine operation, which can vary both within and across machinery. In principle, thermocapillary effects can be minimized by reducing the surface tension dependence on temperature ($\frac{\partial \gamma}{\partial T}$).

Unfortunately, in practice, tuning $\frac{\partial \gamma}{\partial T}$ is confounding due to the interdependence of surface tension on the lubricant composition and additive concentrations. In many situations, solutocapillary and thermocapillary effects can act synergistically to sustain foams. This situation is common when lubricants contain volatile components [22].

The presence of a structural film of adsorbed material can impart finite interfacial rheology in lubricant oils. Interfacial rheology can stabilize foams by retarding foam drainage [23]. Fresh lubricants are almost always devoid of interfacial rheology. However, lubricants can develop interfacial rheology and foam over use as a result of oil aging, oxidation and the adsorption of exogenous contaminants [24]. Eliminating this problem is challenging as the build of interfacial rheology depends on the duration of use and the specific operating conditions of the lubricant.

3. Enhancing Antifoams

Antifoams are additives in the form of solid particles, liquid droplets or a combination of the two that are added to the lubricant to accelerate breakup of foams. The effectiveness of lubricant antifoams and the consequent destabilization of foams are often limited by the following issues: filtration, degradation, inversion and settlement.

Lubricants in high-performance applications are almost always continuously filtered to remove harmful particulates [1,25,26]. Antifoams are also unfortunately removed in the process. Optimizing the filter surface chemistry to prevent unwanted adsorption of antifoams can reduce antifoam removal [27]. However, the conflicting requirements in filter design—removing particles that are as small as possible while retaining as much antifoam as possible—makes it challenging to eliminate this problem. Antifoams are known to degrade

and become disproportionate over time. The appropriate antifoam size and structure (particularly for solid and mixed antifoams) is crucial for their effectiveness [26,28].

Completely eliminating antifoam disintegration is challenging, particularly for liquid and mixed antifoams, as this is often an unavoidable outcome accompanying their mechanism of action (such as during bridging stretching) [29]. Antifoams can also become profoamers [17,30,31]—a process that is referred to as inversion. Though infrequent, this phenomenon can be particularly problematic due to its potential to cause dramatic changes in foam stability. Antifoam inversion can happen at high temperatures due to changes in the antifoam surface characteristics and due to changes in the surface properties of the lubricant, including due to the influence of other additives. Eliminating this problem depends on a good understanding of the interfacial properties, which is often difficult due to the multitude of interdependent factors affecting the results [1].

Antifoams can settle and separate out from the lubricant over time due to gravity. In principle, this problem can be mitigated by density matching and by reducing the antifoam size [1]. The former is practically difficult due to the challenges in tuning the density independent of more important antifoam physical properties, such as the surface tension. The later is also undesirable as smaller antifoams are also less effective (as discussed above).

Overcoming the above-mentioned challenges is necessary to develop foam-resistant lubricants that can serve the needs of modern machinery. Due to the number of interdependent mechanisms that drive lubricant foaming, it is no surprise that trial and error approaches have had limited success in tackling the above problems. With the advent of big data and machine-learning frameworks [32,33], it is clear that we have viable tools to guide the optimal formulation of lubricants amid a multitude of interdependent requirements.

A necessary step for making this possible lies in addressing a common thread that connects the above-mentioned challenges, which is the need for improved mechanistic understanding of lubricant foaming and antifoaming across different operating conditions, additive types and additive concentrations. This cause will be further helped by the development of novel lubricant and antifoam chemistry [1]. Systematically accomplishing these goals through further research could enable a much needed shift from the existing trial-and-error formulation of lubricants and accelerate the development of foam-free lubricants.

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