Utilising Large Industrial Mixer as a Rheometer- Computational Analysis Using OPENFOAM

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ABSTRACT

Knowing the correlation between the power required to rotate a large industrial mixer and the rheological properties of the fluid within can be of importance to the industry. In this paper we will focus on the concrete truck mixer, which is here used to extract the rheological properties of the fresh concrete, modelled as a Bingham fluid. The uncontrolled flow pattern within the mixer makes this a challenging task. But if possible, such would clearly assist in the decision making at job site for the more difficult casting operations, for example. In this work, the analysis is done using Computational Fluid Dynamics (OpenFOAM). More precisely, the relationship between the Bingham parameters and the required power to rotate the mixer (i.e. the drum) is mapped using CFD. The power is calculated in kilowatts [kW] and can be related to the hydraulic pressure to turn the drum (a.k.a. “slump meter”). Overall, the current work is done to investigate the feasibility of using the truck mixer as a rheometer.

INTRODUCTION

Feasibility studies have been made of using a large industrial mixer, like the concrete mixing truck, as a rheometer[1-3]. For the concrete mixing truck, the registration of data is usually in terms of logging hydraulic pressure required to turn the mixer at a specific rate. Since the pressure is related to movement of piston(s) inside the drum drive motor, work is being conducted (over a time interval), meaning that the hydraulic pressure is related to power (i.e. rate of work). The test procedure usually consists of doing pressure readings at different mixer speeds. With this, a graph of pressure versus mixer speed is obtained. The rheological parameter of the mixer is then extracted by the graph slope H and its point of intersection with the ordinate G. The hope is that these two values relate to the Bingham parameters, namely the plastic viscosity μ and the yield stress τ_0, respectively. Often, encouraging results are reported in using the concrete truck in this manner[1-3]. Here, the power required to rotate the mixer is calculated as a function of rotational speed f, namely 0.03, 0.07, 0.11, 015, 019 and 0.23 rps – revolutions per seconds. This is done at a fixed fluid volume $V = 5.4$ m^3. In addition to this, the effect of yield stress τ_0 and plastic viscosity μ is also analysed.

In this work, the mixer consists of a market-leading commercially available concrete drum, produced in Germany, shown in **Fig. 1**. Its total volume is 15.7 m^3, but the max rated fluid capacity is 9 m^3. In general, the nominal range of mixer speed is between 0 and 14 rpm (i.e.

from 0 to 0.23 rps). The inclination of the mixer relative to the horizontal is 11 degrees. The number of computational cells used for the mixer is about 60.000, but also a high-resolution simulation has been done, which consists of about 400.000 cells for mesh independence analysis[4]. The simulations were performed on resources provided by the Icelandic High-Performance Computing - IHPC (ihpc.is). All computations were done with the CFD simulation software OpenFOAM[5]. Additional information about the technical aspect of the calculation, like solution methods, mesh independence and boundary conditions are available elsewhere[4,6].

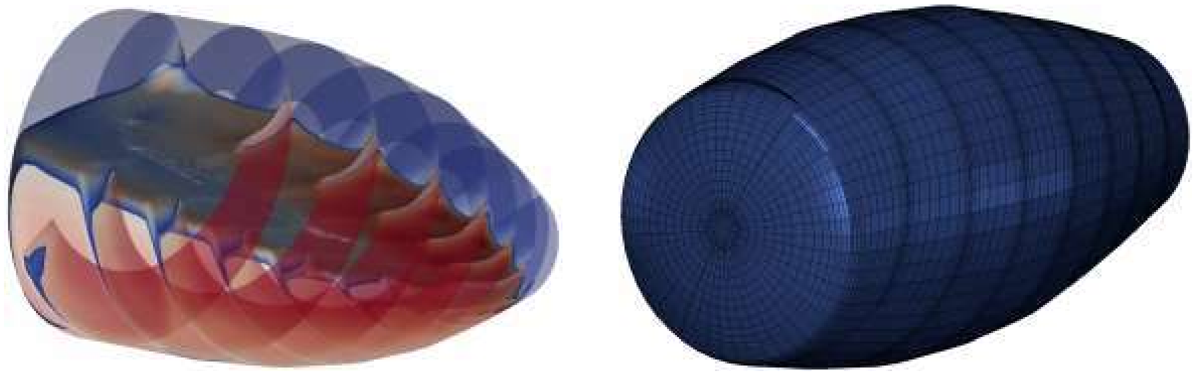

FIGURE 1: The geometry of the mixer that is used in the current work (see also[4,6]).

The shear rate distribution within the concrete sample calculated by[7] $\dot{\gamma} = \sqrt{2\,\dot{\varepsilon}:\dot{\varepsilon}}$ (the term $\dot{\varepsilon}$ being the rate of deformation tensor[8,9]). It should be clear that the profile of shear rate is very variable within the fluid inside the mixer[4]. The constitutive equation used here, consists of the Generalised Newtonian Model, or in short GNM[10]. An example of such model is the modified Bingham model, in which it's benefit is discussed for fresh concrete[11]. As such, in this work, it was programmed into the OpenFOAM framework for future analysis. It should be noted that in the current analysis, it's so-called *c*-parameter is set equal to zero and thus in effect the traditional Bingham model is used in this work.

RATE OF WORK (MECHANICAL POWER)

The volume of a *material body* is here designated with V and its bounding surface with ∂V. This volume V is an arbitrary part of the continua and is named *material volume*[12-14]. The material body represents a fixed number of fluid (or continuum) particles[12-14]. In this work, the material volume is chosen as consisting of all the fluid (here, fresh concrete) inside the mixer, namely with $V = 5.4$ m^3. The rate in mechanical effort (i.e. rate of work) conducted on this material volume V, from its surroundings, is here designated with $\dot{W}$ [J/s] and is given by[12,14]

$$\dot{W}(t) = \iiint_V \rho\, \mathbf{g} \cdot \mathbf{v}\, dV + \iint_{\partial V} \mathbf{t} \cdot \mathbf{v}\, dA \tag{1}$$

Since V is here chosen as all the fluid inside the mixer, the term $\dot{W}$ represents the rate of work (i.e. power) conducted by the mixer in moving/shuffling/rotating/deforming this same fluid inside it. In the above equation, $\dot{W}$ does not including any mechanical friction contribution between the mixer and the rest of the truck (this issue will be addressed shortly). In theory, a negative value for $\dot{W}$ is possible and would entitle that the fluid is doing work on the mixer. The term $\mathbf{t} = \mathbf{n}\cdot\boldsymbol{\sigma}$ is named traction[8,9] and describes the force per unit area [N/m^2] applied at the boundary ∂V, from the outer surroundings of the material volume V (i.e. in this case, applied from the mixer steel wall to the boundary of the fluid). The term $\boldsymbol{\sigma}$ is the (total) stress tensor [Pa]. The term $\mathbf{n}$ is a unit normal vector located at the boundary ∂V pointing away from the material volume V. The terms ρ, $\mathbf{g}$, and $\mathbf{v}$ are the density [kg/m^3], gravity [m/s^2] and velocity [m/s], respectively.

As shown pp. 386 – 389 in[12], through the mechanical energy equation, Eq. 2 below can be directly derived from Eq. 1. It should be noted that the time derivative in Eq. 2 is the total derivative and not a partial derivative.

$$\dot{W}(t) = \iiint_V \rho \frac{d}{dt}\left[\frac{\mathbf{v}\cdot\mathbf{v}}{2}\right] dV + \iiint_V \eta\, \dot{\gamma}^2\, dV = \dot{W}_{KE}(t) + \dot{W}_{\eta}(t) \qquad (2)$$

Here, Eq. 2 is used in calculating the rate of work. The term $\eta = \mu + \tau_0/\dot{\gamma}$ is the apparent viscosity [Pa·s] and as already mentioned, $\dot{\gamma}$ is the shear rate [1/s], μ plastic viscosity [Pa·s] and τ_0 is the yield stress [Pa]. Although $\dot{W}_{\eta}(t)$ is always positive, the same does not apply for $\dot{W}_{KE}(t)$. That is, a negative $\dot{W}_{KE}(t)$ value can be obtained, which means a reduction in kinetic energy[6]. Except during the mixer start rotation (i.e. while the flow has not reached "equilibrium"), the magnitude of $\dot{W}_{KE}(t)$ is in general much smaller than $\dot{W}_{\eta}(t)$.

The model time duration for each case is 20 seconds, which took usually about one or two weeks to simulate on a single computer node, depending on rheological values used. This means that each power profile by Eq. 2 has a duration of 20 seconds. By time integrating Eq. 2 as shown with Eq. 3, only the latter part of the 20 seconds power curves are utilised.

$$P = \frac{1}{20\text{ s} - 10\text{ s}} \int_{10\text{ s}}^{20\text{ s}} \dot{W}(t)\, dt = P_{KE} + P_{\eta} \qquad (3)$$

It should be clear that both P and $\dot{W}(t)$ are rate of work (i.e. power) with the units of Watts [W]. Here, the former variable is a time integration to get a well-defined average value, while the latter variable represents an instantaneous value, valid at the time t. By starting the integration in Eq. 3 at 10 seconds, and not at 0 seconds, is made due to the fact that equilibrium in rate of wok (to the extent what is possible) is usually obtained at 10 seconds[6]. The output of Eq. 3, namely the power $P = P_{\mathrm{KE}} + P_{\eta}$, will be used in this work in assessing the current mixer.

RESULTS

Fig. 2 shows the power $P_t = P + P_0$ as a function of different mixer rotational speed f, yield stress τ_0 and plastic viscosity μ. The term $P = P_{\mathrm{KE}} + P_{\eta}$ is by Eq. 3, while P_0 is a constant, here set equal to 2 kW. The value of P_0 is assumed to come from mechanical friction contribution between the mixer and the rest of the truck, e.g. from gearing box, metal bearing balls and so forth. Its constant value of 2 kW is arbitrarily chosen and could be higher, as well as depend on the concrete load $m = \rho \cdot V$ and/or the mixer speed f, which is not considered here. The benefits of P_0 will be clear in **Fig. 3**, as it will avoid negative G values in the analysis.

As to be expected, the outcome of **Fig. 2** shows how the power consumption in rotating the mixer, increases with increased rotational speed f. For all cases of plastic viscosity μ = 25 Pa·s, the corresponding curves have a nudge at f = 0.11 rps. However, at and above 75 Pa·s, for all yield stresses τ_0, this nudge does not appear. The reason for this nudge could be some sort of wave resonance, by the helix geometrical shape of the mixing blades inside the mixer (see the left illustration of **Fig. 2**), which becomes dampened with increased plastic viscosity[4,6].

In line with[2,3], the rheological parameter of the concrete truck mixer can be extracted by the slope H and the point of intersection with the ordinate G of the curves in **Fig. 2**. In **Fig. 3**, these H and G values are plotted against the fluid plastic viscosity μ and yield stress τ_0. As shown, a fairly bad correlation is generally obtained. For example, the value $G = 1$ kW can represent a yield stress τ_0 somewhere between 0 and 300 Pa, while $H = 50$ kW·s can represent a plastic viscosity μ anywhere between 25 and 75 Pa·s. Thus, the registered G and H values can represent a wide variety of yield stresses τ_0 and plastic viscosities μ.

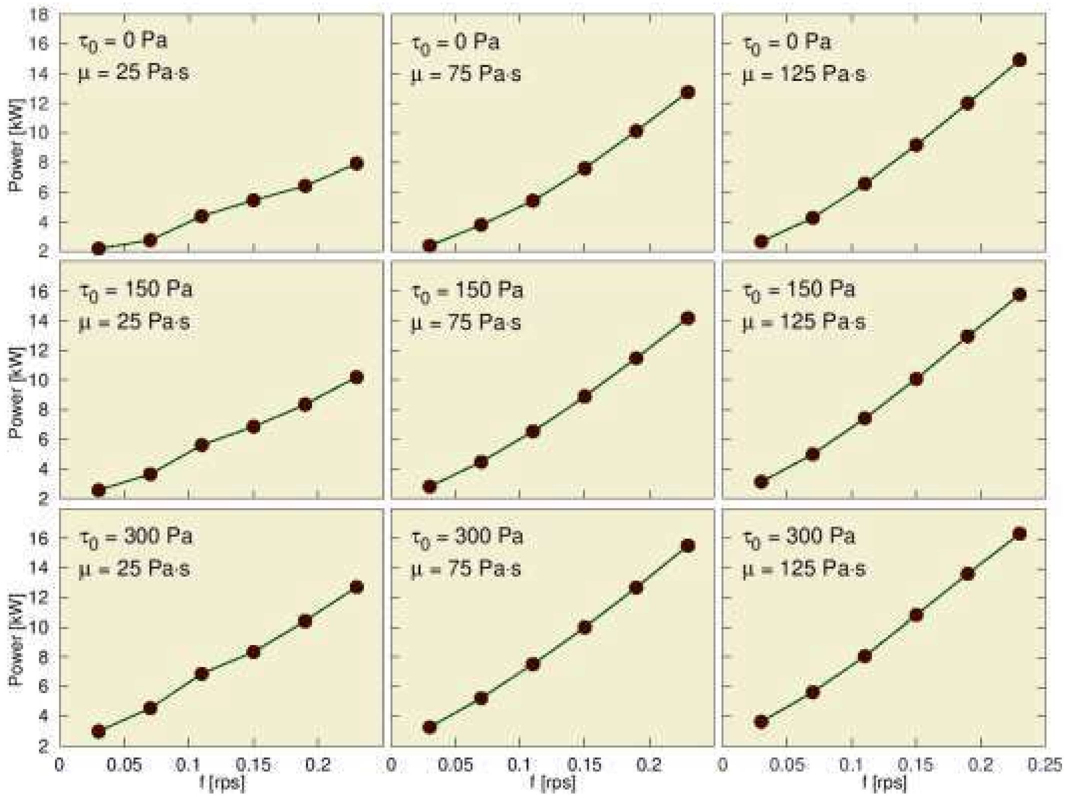

FIGURE 2: Power $P_t = P + P_0$ as a function of mixer rotational speed f.

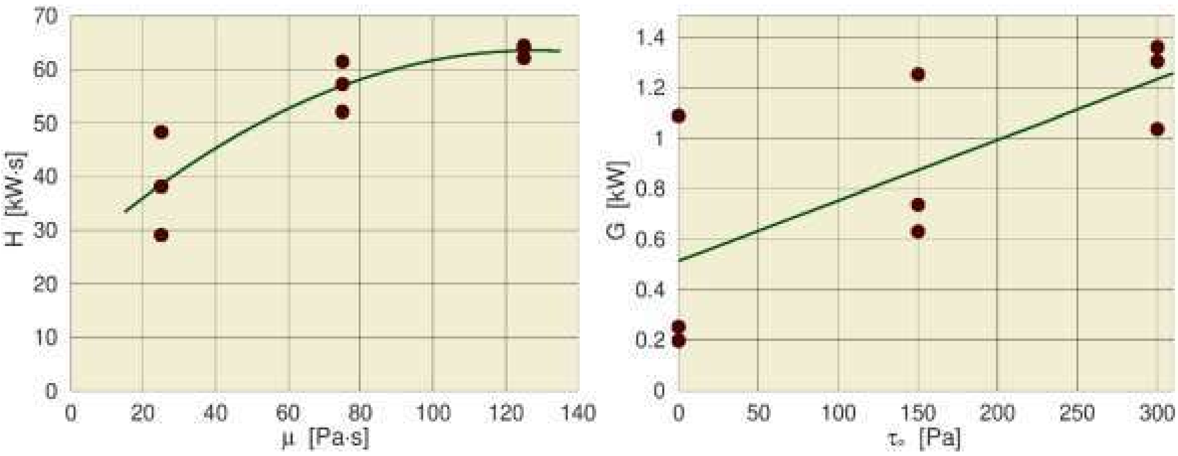

FIGURE 3: The relationship between H and μ (to the left) and G and τ_0 (to the right).

It should be noted that for the right illustration of **Fig. 3**, all the three top points apply for the plastic viscosity value of 25 Pa·s. Thus, by omitting these three points, a much better correlation between the G value and the yield stress τ_0 is obtained. Thus, it is clear that for some cases, it is very well possible to obtain fairly good yield stress values from the mixer. However, obtaining plastic viscosity values seems to be more difficult.

SUMMARY AND CONCLUSION

In this work, the relationship between the power requirement (in kW) in rotating an industrial mixer and the Bingham values of the fluid inside it, has been analysed using OpenFOAM. More precisely, the power has been calculated at different mixer speed f and different rheological parameters μ and τ_0, at a constant volume of fluid V. The resulting power curves has been used in calculating the slope H and point of intersection with the ordinate G. By comparing these two values with the applied yield stress τ_0 and plastic viscosity μ, it is clear that it is not straightforward to use this specific mixer (i.e. the truck mixer) as a rheometer. However, in some cases, it is very well possible to obtain good yield stress values from the truck.

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