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NOTE ON ROTATING CUP ATOMIZER THEORY

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Abstract. *Rotating cup atomizers, along with other rotary atomizers, are used in industrial furnaces, as they generate droplets of a nearly uniform size and process a high capability in handling large fuel flow rates. This work compares the existing droplet size distributions available in the literature and based on Tanasawa et al. fully experimental models with an extension of a theoretical model primarily developed for fan spray atomizers which has been recently improved for impinging jets and then modified to fit the behavior of* Y-jet *atomizers and pressure swirl atomizers. The results were found quite satisfactory for case of reasonably viscous fluids but not so for low viscosity ones the reason possibly being that Tanasawa's correlation does not contain the viscosity coefficient.*

Keywords: *rotating cup and disk atomizers, sprays, droplets*

1. Introduction

Rotating cup atomizers, along with other rotary atomizers, find a lot of use in industrial furnaces, their main advantages being the generation of droplets of a nearly uniform size and a high capability in handling large fuel flow rates.

As it is well known, these atomizers can generate droplets according to three mechanisms: I – Direct Droplet Formation (at a very small supply rate, a liquid torus is formed around the edge of the rotating disk whose diameter is determined mainly by the equilibrium conditions between centrifugal and surface tension forces; II – Disintegration by Ligament Formation (at an increased rate of supply, the state of formation of droplets singly at the bulges of the torus may transit into the formation of complete thin jets or ligaments, which will break up and contract by surface tension action generating the droplets); and III – Disintegration by Film Formation (still further increasing the rate of supply, a condition can be reached when the number of ligaments cannot increase anymore nor can they grow in thickness, thus generating a liquid sheet).

The present paper intends to compare the existing droplet size distributions for rotary atomizers operating in the filmwise atomization mode, available in the literature and based on Tanasawa et al., 1978, models, (fully built on experimental data), with an extension of a theoretical model primarily developed by Dombrowski and Johns, 1963, for fan spray atomizers which has been recently improved by Couto et al. for impinging jets and then modified to fit the behavior of *Y-jet* atomizers and pressure swirl atomizers (Couto and Bastos-Netto, 1991; Couto et al., 1999; Couto et al., 1997b; Couto et al., 1997a and Couto and Bastos-Netto, 2000).

2. Problem description

Rotating disk or cup atomizers are those in which a liquid is fed on a rotating surface spreading nearly uniformly under the centrifugal force effect. This rotating surface might be a flat disk, a vaned disk or a slotted wheel. The schematics of a rotating cup atomizer can be seen in Fig. 1. The diameter of these devices can vary from 25 to 450 mm and they rotate in frequencies up to 1000 Hz for smaller disks and up to 200 Hz for the larger ones, their atomizing capability being within the range from less than 3 kg/h up to 1.4 kg/s, Lefebvre, 1989.

According to Masters, 1978, rotary atomizers will find increased use in industrial spray-drying operations. This is due to new developments in the design of these devices, more reliable driving systems and better wheel operation. Significant advances have been made in handling high feeding rates (up to 40 kg/s) at high wheel peripheral speeds that yield very fine atomization ($SMD < 20$ μm).

This system is quite versatile and effective in the atomization of liquids within a broad range of viscosity. An important aspect of this kind of atomizer is that the thickness of the film formed by the liquid sheet upon leaving the device can be effectively controlled through the change of the liquid flow rate and/or the rotational

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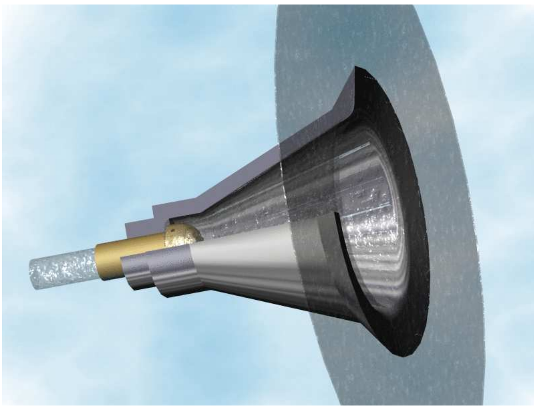

Figure 1: Rotating disk atomizer schematics.

speed. This enables their use in multi fuel engines. However these atomizers can be tricky to build for they require precise balancing (to avoid excessive vibration) and good quality sealing (to preclude leaks). These requirements make them hard to build and, obviously, expensive.

According to Karim and Kumar, 1978, for a uniform film thickness (and hence a more uniform drop size distribution) to be achieved in rotary atomizers, the following conditions should be met: a – the centrifugal force should be large compared to the gravitational force; b – the cup rotation should be vibrations free; c – the liquid flow rate should be kept constant; and d – the cup surface should be smooth. Therefore it is assumed that the speed the liquid arrives at the rim is always the same. If the rate of rotation is changed the speed of the liquid at the rim will change accordingly. Further, if the rate is held constant an increasing in the liquid mass flow rate will lead to an increase in the film thickness at the rim, not to an increase of the liquid velocity at the rim. Notice that this is an approximation.

3. Governing equations

Hinze and Milborn, 1950, have shown that the thickness of the liquid layer at the rim cup, h_0, can be given by:

$$h_0 = \left(\frac{3\mu_l Q}{2\pi\rho_l(\omega r)^2 \sin(\varphi)} \right)^{\frac{1}{3}} \tag{1}$$

where Q [m^3/s] is the liquid volume flow rate, μ_l [kg/m-s] is the liquid dynamic coefficient of viscosity, ω [rad/s] is the cup angular speed, r [m] is the maximum radius of the cup, ρ_l [kg/m^3] is the liquid density and φ is the cup half cone angle. Tanasawa et al., 1978, have suggested (for the film formation type of transition), the following expressions for the critical flow rate, Q_T:

$$Q_T = 306.6\sqrt{d} \left(\frac{1}{n}\right)^{\frac{2}{3}} \left(\frac{\sigma}{\rho_l}\right)^{\frac{5}{6}}, \qquad \text{for} \quad \frac{d \cdot \rho_l}{\mu_l} > 3000 \ s/m \tag{2a}$$

$$Q_T = 81.23 \left(\frac{d}{n}\right)^{\frac{2}{3}} \left(\frac{\sigma}{\rho_l}\right) \left(\frac{\rho_l}{\mu_l}\right)^{\frac{1}{3}}, \qquad \text{for} \quad \frac{d \cdot \rho_l}{\mu_l} < 3000 \ s/m \tag{2b}$$

where d is the maximum diameter of the cup ($d = 2r$), σ [kg/s^2] is the liquid surface tension and n [Hz] is the cup rotation rate.

The liquid mean radial velocity, U_0, was also calculated by Hinze and Milborn, 1950, who obtained

$$U_0 = \left(\frac{\rho_l \omega^2 \sin(\varphi) Q^2}{12\pi^2 \mu_l r} \right)^{\frac{1}{3}} \tag{3}$$

U_0 is calculated using Q_T as given either by Eq. 2a or Eq. 2b and it is held constant.

Choosing U_C to be the cup tangential speed at the rim,

$$U_C = \omega r \tag{4}$$

Then the liquid velocity field distribution, U_i, immediately upon leaving the cup, can be written as:

$$U_i = \sqrt{U_C^2 + U_0^2} \tag{5}$$

The diameter of the ligaments, d_l, formed by the breaking up of the liquid sheet upon leaving an atomizing device according to the mechanism proposed by Dombrowski and Johns, 1963, for a fan spray atomizer, which was modified by Couto et al to include other kinds of atomizers (Couto and Bastos-Netto, 1991; Couto et al., 1999; Couto et al., 1997b; Couto et al., 1997a and Couto and Bastos-Netto, 2000), can be written (for large Weber Numbers) as:

$$d_l = 0.9614 \left(\frac{K^2 \sigma^2}{\rho_{air} \rho_l U_i^2} \right)^{\frac{1}{6}} \left(1 + 2.6 \mu_l \sqrt[3]{\frac{K \rho_{air}^4 U_i^8}{72 \rho_l^2 \sigma^5}} \right)^{\frac{1}{5}} \tag{6}$$

where ρ_{air} [kg/m^3] is the surrounding air density and K is the "nozzle parameter", which Dombrowski and Johns, 1963, calculated for fan-spray atomizers only, and which has been modified for other kinds of atomizers (Couto and Bastos-Netto, 1991; Couto et al., 1999; Couto et al., 1997b; Couto et al., 1997a and Couto and Bastos-Netto, 2000).

As a fan-spray atomizer is assumed to generate a plane sheet, those authors took the thickness h at any section y from the injection point to be given by $h = K_1/y$, where K_1 was a constant (Couto et al., 1997b). For a radiating conical sheet, the thickness at any section was considered to be given by $h = K_1/X$, where X was the coordinate along the sheet. Dombrowski and Johns, 1963, used $K_2 = ht$ where K_2 was a constant and t was the time. Therefore $K_2 = K_1 t/X = K_1/U$, where U was the liquid propagating velocity.

The sheet develops in such a way that $hX = K_1 = Const.$ The only way for this to be achieved is that, at any coordinate $X = nh_i$ (where n is any positive number and h_i is the initial film thickness where it turns around to form the cone), the sheet thickness should be equal to h_i/n. Then $K_1 = (h_i/n).nh_i = h_i^2$ and $K_2 = h_i^2/U$ (Couto et al., 1997b).

Here, in the case of a rotary cup atomizer, this thickness h_i is the film thickness as the fluid leaves the cup, i.e., $h_i \approx h_0$. Further, given the above mentioned approximation that the speed the liquid arrives at the rim is always the same, $U \approx U_0$. Therefore

$$K = \frac{h_0^2}{U_0} \tag{7}$$

for rotating cups or disks, so that Eq. 6 yields

$$d_l = 0.9614 \left(\frac{h_0^4 \sigma^2}{\rho_{air} \rho_l U_0^2 U_i^2} \right)^{\frac{1}{6}} \left(1 + 2.6 \mu_l \sqrt[3]{\frac{h_0^2 \rho_{air}^4 U_i^8}{72 \rho_l^2 U_0 \sigma^5}} \right)^{\frac{1}{5}} \tag{8}$$

for the diameter of the ligaments, which according to Rayleigh (Lefebvre, 1989) will generate droplets with a *Sauter Mean Diameter*, SMD_1, of

$$SMD_1 = 1.89 d_l \tag{9}$$

However, if the Sauter Mean Diameter is calculated using the correlation obtained by Tanasawa et al., 1978 (also shown by Lefebvre, 1989), then

$$SMD_2 = \frac{15.6\sqrt{Q}}{n} \left(\frac{\sigma}{\rho_l r^2} \right)^{0.4} \tag{10}$$

then these experimental results can be compared with those given by Eq. 9.

4. Results and conclusions

For comparison with the results of Tanasawa et al., 1978, obtained for a rotating disk, one chooses $\varphi = 90^o$ and $d = 0.1$ m in the above equations and the fluids characteristics taken from Lefebvre, 1989, for light and medium fuel oils as shown in Tab. 1.

Table 1: Atomizing fluids properties (taken from Lefebvre, 1989).

Description	ρ_l [kg/m^3]	σ [kg/s^2]	μ [kg/m-s]	T [K]
Fuel oil (medium)	930	0.0230	0.17200	313
Fuel oil (light)	916	0.0230	0.04700	313
Water	1000	0.0717	0.00085	300

For both kinds of oils $\rho_l d/\mu_l < 3000$, therefore Eq. 2b was used to establish the transition into film formation which, for $n = 500$ Hz and the above properties, yield critical flow rates of $Q_T = 1.31 \times 10^{-4}$ m^3/s (i.e., 472 L/h) for the medium class oil and $Q_T = 1.88 \times 10^{-4}$ m^3/s (i.e., 677 L/h) for the light class oil. However, for water $\rho_l d/\mu_l > 3000$, so that Eq. 2a was used yielding $Q_T = 5.41 \times 10^{-4}$ m^3/s (i.e., 1950 L/h).

Hence $SMD1$ and $SMD2$ as given by Eq. 9 and 10, are applicable for flow rates above those values only.

Figure 2 shows that $SMD1$ and $SMD2$ run nearly paralell to each other in the region of validity of both models (i.e., for $Q > Q_T$). This is so because Tanasawa's model (Eq. 10) does not include viscosity dependencies other than the ones used in establishing the critical transition flow rates presented in Eq. 2a and 2b.

Therefore, for fluids with smaller values of viscosity (other parameters being alike), $SMD1$ and $SMD2$ should display convergence such as the one shown in Fig 3 for a light class oil.

Notice however that, for fluids still less viscous but possessing much higher surface tension (such as water), the lack of sensitivity of Tanasawa's model for changes in viscosity is aggravated with its insentitivity to large changes of surface tension (Fig. 4).

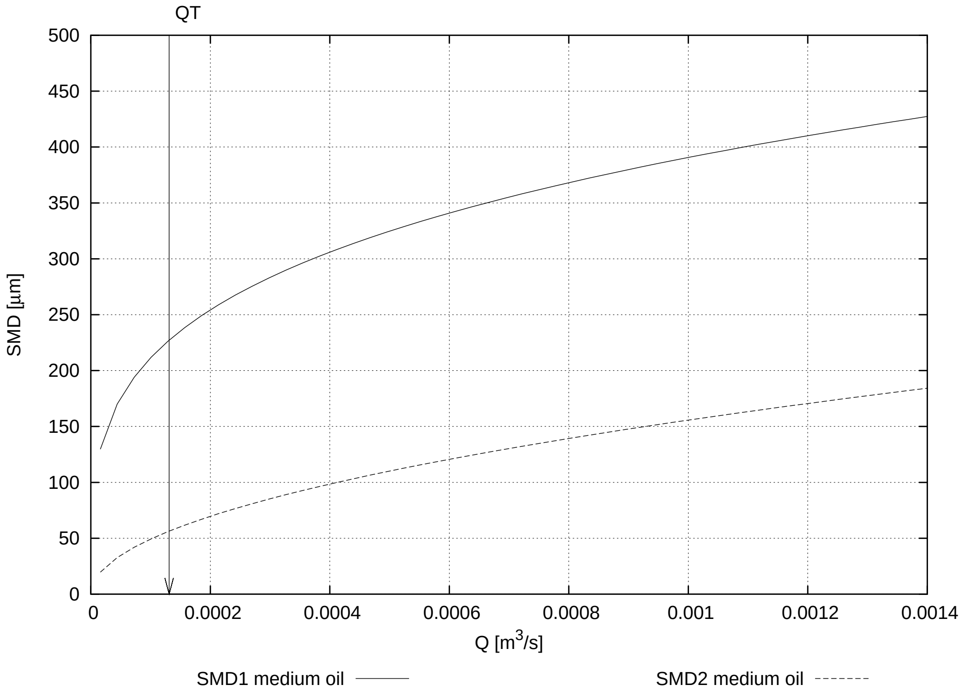

Figure 2: SMD_1 and SMD_2 vs Q for $n = 500$ Hz (medium class oil).

Figure 5 shows the behavior of the critical transition flow rate Q_T with the rotation rate n for the medium class oil in the above described conditions ($d = 0.1$ m, Tab. 1).

Finally Fig. 6 depicts $SMD1 - SMD2$ vs Q and n for light class oil. As expected, it shows that Tanasawa's correlation ($SMD2$) and these authors model ($SMD1$) match reasonably well in the mesa region of that figure.

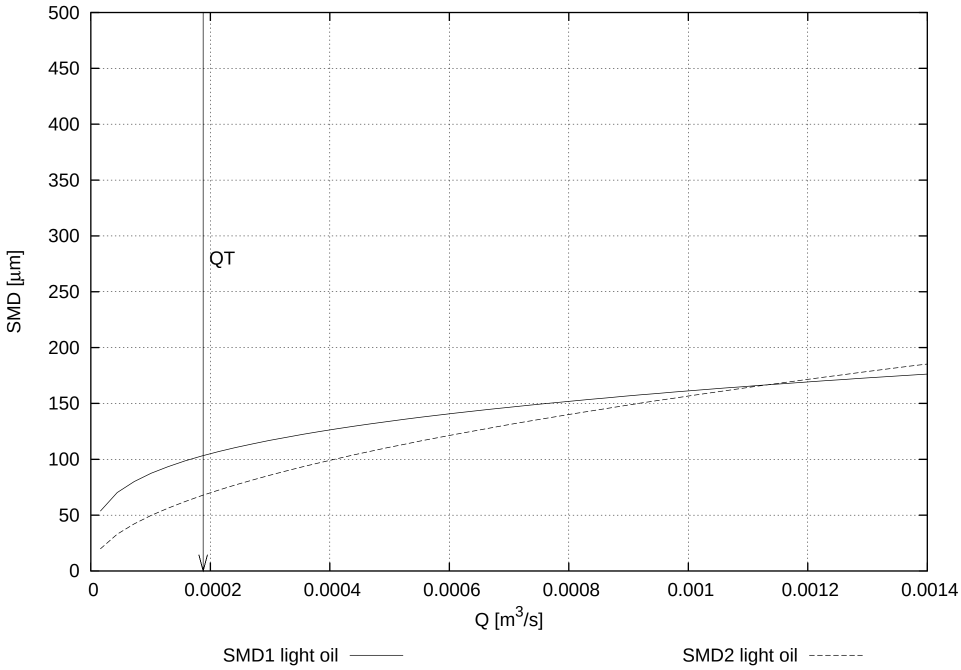

Figure 3: SMD_1 and SMD_2 vs Q for $n = 500$ Hz (light class oil).

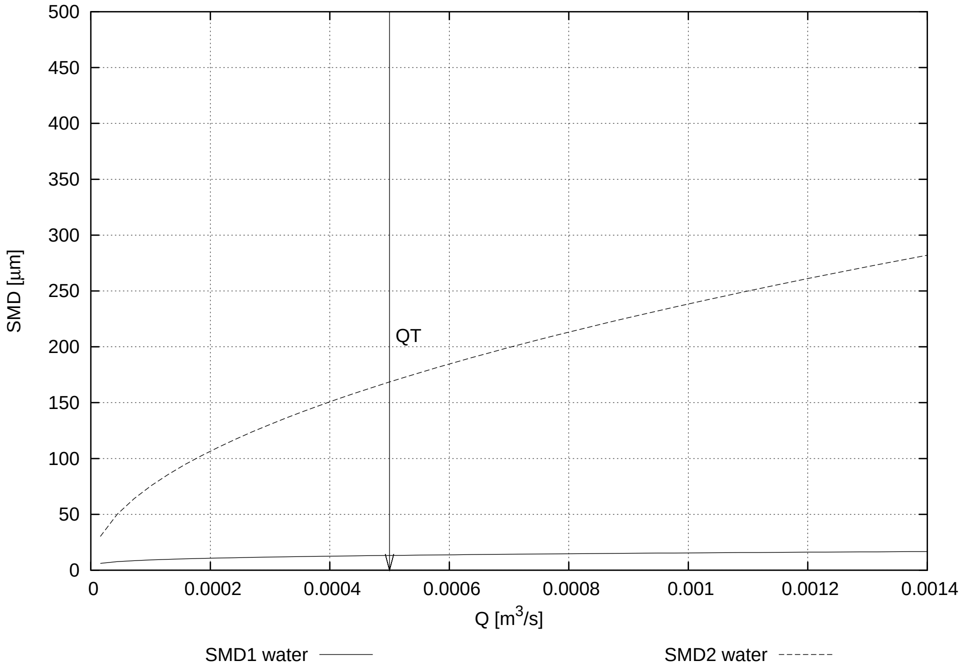

Figure 4: SMD_1 and SMD_2 vs Q for $n = 500$ Hz (water).

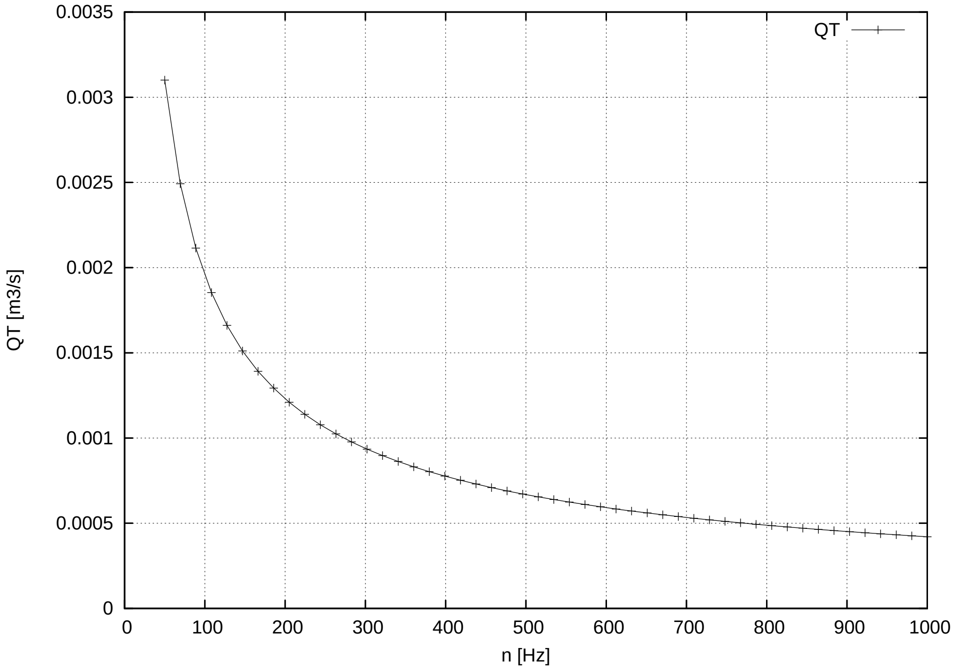

Figure 5: Critical volume flow rate, Q_T, vs rate of rotation, n (medium class oil).

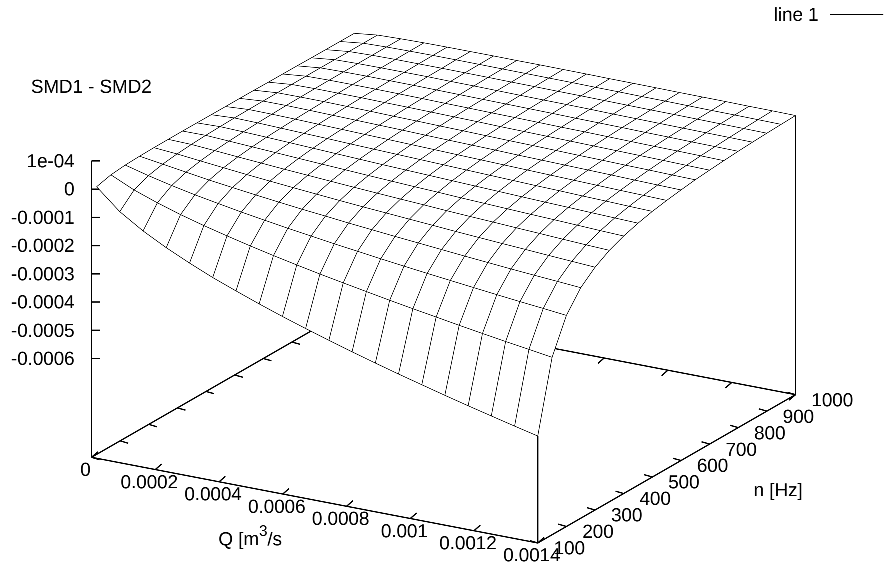

Figure 6: $SMD1 - SMD2$ vs Q and n (light class oil).

5. Acknowledgements

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