CHARACTERISTICS OF BLACK LIQUOR SPRAY DROPLETS

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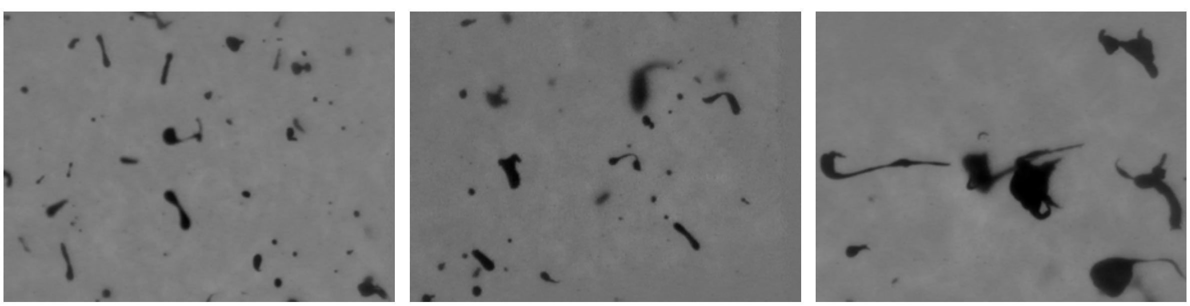
ABSTRACT

The shapes and sizes of droplets in high solid content black liquor sprays were measured using image analysis. The average aspect ratio and sphericity were found to be approximately 3.6 and 0.87. These values were used to calculate the effect of droplet size and shape on the particle flight path and heat transfer compared to the situation in which the spray was formed from spherical particles. It was found that the flight path of the spray was only slightly shortened for non-spherical particles. Terminal velocity and relaxation time of single particles were 40-70% smaller for non-spherical particles than for spherical particles. Heat transfer to the spray was calculated assuming isothermal particle temperature. The heat transfer was 5-25 % higher for the spray of non-spherical particles than for the spray of spherical particles.

INTRODUCTION

The spraying of black liquor into a recovery boiler furnace is of paramount importance for the efficiency of the heat and chemical recovery. The spraying differs in many ways from the conventional spraying of other fuels. The solid content of black liquor may be more than 80%. The viscosity of sprayed black liquor varies between 50-300 mPa•s. The spraying temperature is often 15-20°C above the boiling point of black liquor to keep the viscosity at an acceptable level. Because of the high viscosity of black liquor, large nozzles are used for spraying. When the spraying pressure is sufficiently low, the mean particle size is consequently large and the spray contains a lot of large non-spherical droplets. Measurement of the size and shape of black liquor spray droplets is not possible in the furnace of a recovery boiler. Instead, Kankkunen *et al.* [1] measured the size and shape of particles in a wide series of measurements carried out in a spray test chamber. The mass median diameter, assuming spherical shape, was typically between 5 and 14 mm. The aspect ratio of an equivalent ellipsoid, substituting analyzed shapes, was approximately 3.6. A typical image of the particles formed is presented in Figure 1. Image height is 75 mm.



Case 1. ΔT_e=17.8ºC, m=4.3 kg/s | Case 5. ΔT_e=17.4ºC, m=5.2 kg/s | Case 9. ΔT_e=13.8ºC, m=6.1 kg/s

Figure 1. Black liquor particles at the distance of 4 meters from the nozzle; high, medium and minimum flashing cases.

The objective of this paper is to study the shape of black liquor spray particles and the effect of this on their flight path and heat transfer. The focus of interest is on the spray test chamber tests carried out and the real furnace situation is considered only shortly. Even though the circumstances in these two cases are very different, the essential behavior of particles can be studied by calculations with proper equations and initial data. This study handles the particles during the first moments of flight to a maximum distance of 4 meters from the nozzle. In this case, particle swelling (in the furnace) and drying are not as important as they would be over longer distances.

Circumstances in the spray test chamber

Figure 2 presents the test arrangement and the spray test chamber. Black liquor was sprayed into the spray test chamber with three mass flow rates and three temperatures. The velocity near the nozzle was measured in the spray center line. Particle size and shape was measured at the distance of 4 meters from the nozzle. The temperature of the chamber was 80°C. The spraying arrangement is more accurately presented by Kankkunen *et al.* [1]. Velocity measurements are presented by Miikkulainen *et al.* [2]. Black liquor temperature and excess temperature above boiling point, viscosity, mass flow rate and measured center line velocity are presented in Table 1.

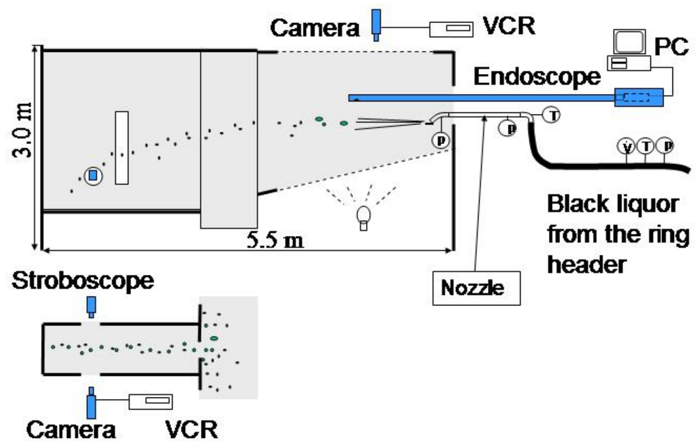


Figure 2. The spray test chamber

Table 1. Spraying parameters

Case	T	ΔT_e	μ	m	u
	[ºC]	[ºC]	[mPa·s]	[kg/s]	[m/s]
1	135	17.8	122	4.3	14.8
5	135	17.4	154	5.2	12.2
9	131	13.9	153	6.1	9.7

Approximate Reynolds numbers in the spray test chamber are between 400 and 10000 for particle sizes of 1 to 15 mm. In the furnace, consequent Reynolds numbers are smaller. Reynolds number values are never on the Stokes area, but in the intermediate regime or Newton's law regime.

Shape and size of black liquor particles

The shape of particles was defined by an image-analysis system explained more precisely by Kankkunen *et al.* [1,3]. All analyzed particles were reduced to 3-dimensional ellipsoids to enable the calculation of their volume and surface area. Two shape definitions, aspect ratio and sphericity, were found to be the most useful shape characteristics. The aspect ratio is defined by the equation

$$\Gamma = \frac{L}{d_e}, \quad (1)$$

where L is the major axis of an ellipsoid and d_e the minor axis of an ellipsoid. Sphericity is defined by the equation

$$\psi_w = \frac{s_S}{s_P}, \quad (2)$$

where S_S is the surface area of an equal-volume sphere and S_p is the surface area of the particle.

Measured average aspect ratio and sphericity for minimum, medium and maximum flashing cases are presented in Table 2. The average aspect ratio is fairly constant, between 3.4 and 3.8. The average sphericity is also fairly constant, about 0.87.

The Sauter mean diameter of non-spherical black liquor spray particles was earlier measured by Kankkunen *et al.* [3] as presented in Table 2. The typical Sauter mean diameter of non-spherical particles was found to be 4.2 mm, for the average test case.

Table 2. Average shape parameters and Sauter mean diameter for non-spherical particles

Case	*Γ*	*ψ*	*SMD*
			mm
1	3.46±1.79	0.87±0.11	3.6
5	3.38±1.73	0.88±0.11	4.2
9	3.76±2.07	0.86±0.12	7.7

Drag coefficient for spherical and non-spherical particles

The drag coefficient for spherical particles is defined by Perry [4]. The equation is in the intermediate regime

$$C_D = \frac{24}{\mathrm{Re}}\left(1 + 0.14\,\mathrm{Re}^{0.70}\right) \qquad (0.1<\mathrm{Re}<1000) \qquad (3)$$

and in the Newton's Law regime

$$C_D = 0.445 \qquad (1000<\mathrm{Re}<350000) \qquad (4)$$

The drag coefficient for non-spherical particles is not readily available. The droplet shapes vary a lot and a general shape such as ellipsoid must be chosen. Haider and Levenspiel [5] suggested equation

$$C_D = \frac{24}{Re}\left(1 + (8.1716)^{-4.0655\psi}\, Re^{0.0964+0.5565\psi}\right) + \frac{73.69\, Re\, e^{-5.0748}}{Re + 5.378 e^{6.2122\psi}} \qquad (5)$$

for non-spherical particles.

Values of the drag coefficient are presented in Figure 3. There seems to be essential differences between spherical and non-spherical particles when the Reynolds number is higher than 100.

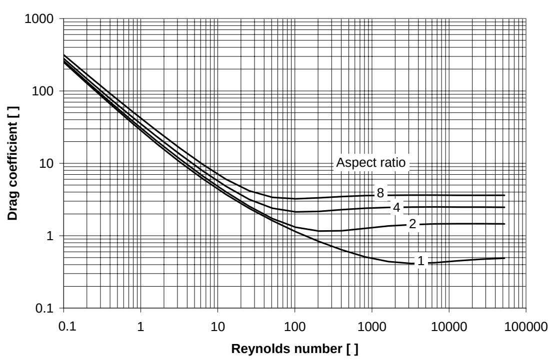


Figure 3. C_d for spherical and non-spherical particles.

The above equations enable calculation of terminal velocity and relaxation time. They are presented in Figures 4 and 5. Terminal velocity and relaxation time of single particles were found to be 40-70% smaller for non-spherical particles than for spherical particles.

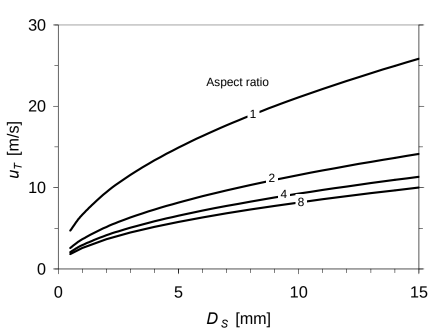


Figure 4. Terminal velocity

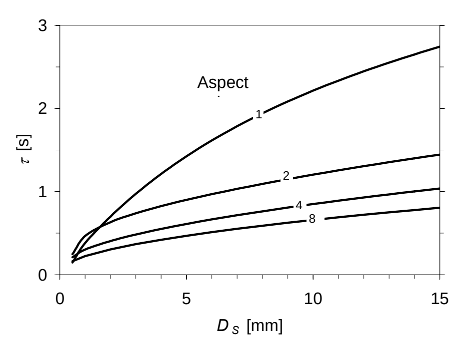


Figure 5. Relaxation time

Heat transfer of spherical and non-spherical particles

Convection heat transfer can be calculated for particles by the equation

$$h = \frac{Nu \lambda_g}{L} \tag{6}$$

where Nu is Nusselt number, λ_g is heat conductivity and L is characteristic dimension of the particle. The Nusselt number for spherical particles is defined according to Incropera and de Witt defined by the equation

$$Nu = 2 + \left(0.4\,Re^{1/2} + 0.06\,Re^{2/3}\right) Pr^{0.4} \left(\frac{\mu_g}{\mu_s}\right) \tag{7}$$

where Pr is Prandl number, μ_g is viscosity of gas and μ_s is the gas viscosity in the surface of the particle. The Nusselt number for cylinder-shaped particles is defined by the equation

$$Nu = 0.3 + \frac{0.62\,Re^{1/2}\ Pr^{1/3}}{(1+(0.4/Pr)^{2/3})^{1/4}} \left[1 + \left(\frac{Re}{28200}\right)^{5/8}\right]^{4/5} \qquad RePr > 0.2 \tag{8}$$

The Nusselt number for ellipsoids is somewhere between these.

The Biot number defines the importance of internal and external heat transfer and is defined by the equation

$$Bi = hL/\lambda\ , \tag{9}$$

where h is heat transfer coefficient, L the characteristic dimension of the particle and λ heat conductivity. The value of the Biot number for black liquor particles is around 1, so both the internal and external heat transfer are important. A transient heat transfer calculation would normally be necessary; however, when drying on the surface of the particles keeps the temperature constant, a transient heat transfer calculation is not necessary during the first few tenths of the first second. In the furnace, radiation is effective and transient heat transfer must be taken into account.

Spray

All above, except for the Sauter mean diameter, we were considering a single particle surrounded by gas. Real situations are different; near the nozzle there is a liquid sheet, which finally breaks up and forms a spray. At a distance of less than two meters from the nozzle, particles are located near each other, but gradually the distance between particles increases. The spray tends to widen e.g. because of the original direction and unevenness of the velocity field in the liquid and the gas phase. The higher-velocity spray accelerates the surrounding gas velocity, which leads to a gas flow from the surroundings to the spray. This gas flow hinders particle size classification caused by gravity. Furthermore, the particle density of the spray decreases and the suction effect at spray boundaries looses its intensity. At the distance of 4 meters from the nozzle, the height of the spray is less than 1 meter and it is supposed that no significant classification has occurred.

Table 3 presents roughly average spray particle density of the typical case at varying distances from the nozzle. Spray velocity (12.2 m/s), the particle size distribution (MMD 6.6 mm) and mass flow rate in the spray center line are obtained from Kankkunen *et al.* [1]. The particle distance is small and the consequent effect on each other is high. It may be helpful, bearing in mind the high mass flow rate, to calculate the spray flight path at the beginning without taking into account the air resistance.

Table 3. Particle densities in the spray center line

Distance to Spray nozzle	Spray Width	Spray height	Density Particle/cm3
1 m	0.02	0.24	17.0
2 m	0.03	0.49	4.2
3 m	0.05	0.73	1.9
4 m	0.07	0.98	1.1

These high particle densities generate turbulence, which augments convection heat transfer. However, the chamber temperature was measured outside the spray; the temperature inside the spray is higher than the temperature measured.

Spray flight path and heat transfer simulation

The flight path of the spray was calculated without air friction for the first two meters, and with 50% of the air resistance after that. Sauter mean diameter was used as the particle size of each test case. Results are presented in Figure 6. The flight path of the spray is only slightly affected by particle shape during the first four meters of flight. The effect is smaller in the furnace, where gas density is only 0.25 kg/m^3. On the other hand the gas flows in the furnace may disturb the spray and cause increased retardation.

Heat transfer was calculated assuming isothermal particle temperature. Sauter mean diameter was used as the particle size of each test case. Heat transfer from the spray is augmented by 5 to 25% in the test chamber if particles are non-spherical, as presented in Figure 7. In the furnace, the heat transfer is mainly radiation heat transfer. Heat transfer is therefore very effective in increased surface area of non-spherical particles. This increased heat transfer in the furnace lead to faster swelling of non-spherical black liquor particles, which, in practice, affects the flight path.

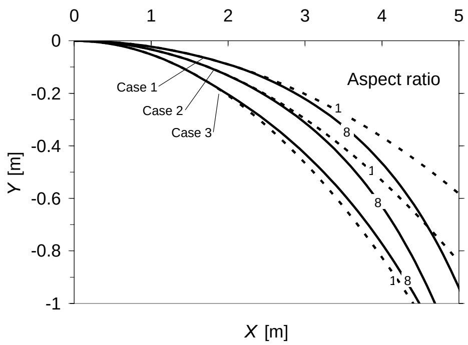


Figure 6. The flight path of particles

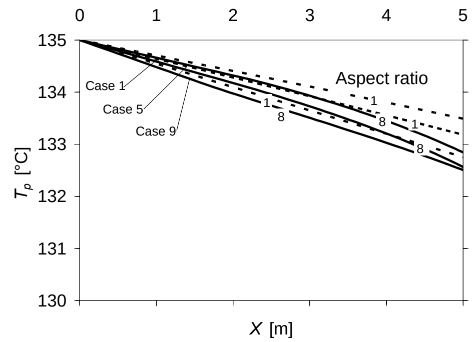


Figure 7. Particle temperature in the chamber.

The accuracy of C_D is assumed to be better than 6 % by Haider and Levenspiel [5]. Because particle shapes are not similar to those used by Haider and Levenspiel is accuracy less good in our case. The accuracy of heat transfer equations is assumed to be 25-30 % by Incropera and de Witt [6]. The accuracy is less good in our case, where a spray is considered instead of single particles.

CONCLUSIONS

The shapes and sizes of droplets forming high solid content black liquor sprays were measured using image analysis. The average aspect ratio and sphericity were found to be approximately 3.6 and 0.87. These values were used to calculate their effect on the spray flight path and heat transfer compared to a situation in which the spray would be formed from spherical particles. It was found that the flight path was slightly shortened for non-spherical particles. Terminal velocity and relaxation time of single particles were 40-70% smaller for non-spherical particles than for spherical particles. The heat transfer from non-spherical particles was only slightly more efficient than from spherical particles. Heat transferred to the spray formed by SMD-size particles gave a 5-25 % smaller heat transfer than that with non-spherical particles. In the furnace situations is different, because of radiation heat transfer.

These calculations will be useful in the next study, in which the heat and mass transfer information of non-spherical particles will be used to study the solidifying process of particles, both in the spray test chamber and furnace.

ACKNOWLEDGEMENTS

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NOMENCLATURE

A	area, m^2
Bi	Biot number, -
C_D	drag coefficient, -
d_e	minor axis of ellipsoid, m
d_S	diameter of equal sphere, m
H	heat transfer coefficient, -
L	major axis of ellipsoid, m
Nu	Nusselt number, -
Re	Reynold's number
S	area, m^2
ΔT_e	excess temperature, ºC
U	velocity, m/s
V	volume, m^3
ψ	sphericity, -
Γ	aspect ratio, L/d_e

Sub-scripts

E	ellipsoid
G	gas
P	particle
S	sphere
s	surface

REFERENCES

1. A. Kankkunen and P. Miikkulainen, Particle Size Distributions of Black Liquor Sprays with A High Solids Content in Recovery Boilers, *IFRF Online Combustion Journal*, pp. 1-21, 2003
2. P. Miikkulainen, M. Järvinen and A. Kankkunen, The Effect of a Furnace Environment on Black Liquor Spray Properties, *Pulp&Paper Canada*, vol. 103, pp. 34-38, 2002.
3. A. Kankkunen, P. Miikkulainen and M. Järvinen, Shape Characteristics of Non-Spherical Black Liquor Droplets, *Proc. International Chemical Recovery Boiler Conference*, vol. 1, pp. 1-9, 2004
4. R.H. Perry, *Perry's chemical engineers' handbook*. McGraw-Hill, 1997
5. A. Haider, O. Levenspiel, Drag Coefficient and Terminal Velosity of Spherical and Nonspherical Particles, *Powder Technology*, vol. 58, pp. 63-70, 1988
6. F. P. Incopera, D.P. de Witt, *Fundamentals of Heat and Mass Transfer*, John Wiley & Sons, 1985