Cavitation-treatment times of a liquid

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An explorative study is conducted to enhance the insight in cavitation-treatment times of molten aluminium. A theoretical analysis is done and a simple model is made. An experimental setup resembling the treatment in a permanent volume leads to observations and some measurements. The measurements serve as a basis for a simple Computational Fluid Dynamics model (CFD) and the observations are used to verify the CFD and enhance the analytical model. A theory is formulated about the treatment time. Although based on rather inaccurate measurements, the CFD model predicts the flow pattern reasonably well.

1. Introduction

Cavitation is used during the continuous casting process of aluminium to improve the material properties. Due to cavitation, generated by a sonotrode, aluminium is degassed and its grain structure refined [1]. A flow is induced by a downward jet, which is produced by the cavitation. Little is known about the time it takes to treat a certain volume [2]. The research question that is focused on is: "*How long does it take to treat 99% of a certain volume?"*

2. Method

A sonotrode producing a zone of cavitation is submerged into a beaker (diameter of 75, 95, 100, 125 mm) filled with water with a diameter/height ratio of 1 **(figure 1)**. Water is used instead of molten aluminium for safety, costs and transparency. The kinematic viscosity of water is in the order of magnitude of that of molten aluminium, giving about the same Reynolds-numbers. To visualize the flow (streamlines) ink is injected in different places in the volume.

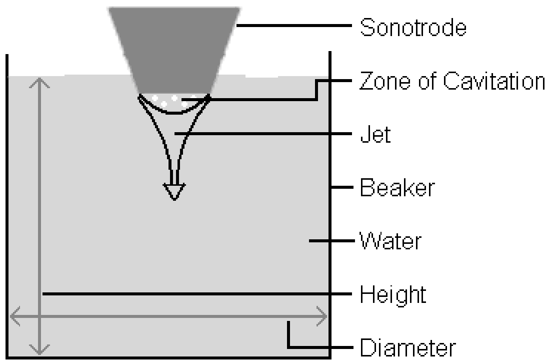

Figure 1: Experimental setup

In order to investigate flow phenomena, some new parameters are introduced:

Treatment time: The time it takes to treat 99% of the volume.

Mixing: The exchange of mass between the treated volume and untreated volume. If the volume of liquid passes through the cavitation zone, it is considered to be 100% treated. If then, this volume becomes "diluted" by the liquid from the untreated volume, it can be considered mixed or partially treated. This mixing is caused by turbulence, not by diffusion.

Minimal treatment time ($t_{minimal.treatment}$): Time it takes to treat the entire volume of the liquid when no mixing occurs. Each unit volume is considered untreated unless it has passed the cavitation zone. If Q is the flow rate through the cavitation zone and V the total volume of the liquid, $t_{minimal.treatment} = V/Q$

Circulation time ($t_{circulation}$): Minimum time required to reach the situation when each unit volume entering the cavitation zone is not 0% treated.

Dead zones: Zones with no interaction with the rest of the liquid, except by diffusion. These lead to very long treatment times.

Jet speed: The maximum flow velocity in the downward jet under the sonotrode.

A differential equation **(1)** is formulated for the fraction of untreated liquid based on following assumptions:

Table 1: Assumptions for Eq.(1)

1	On average, all liquid follows a sequential path, i.e. liquid leaving a zone first will return to the zone first.
2	No dead zones are present
3	The moment the water flows through the cavitation zone it is 100% treated.
4	The flow is fully developed.

$$-\frac{Q}{V}\,p(t-t_{circulation}) = \frac{dp}{dt}, \quad p(t-t_{circulation} \le 0) = 1 \tag{1}$$

Q = flow rate through the cavitation zone
V = total volume
p = fraction of untreated liquid
$t_{circulation}$ = circulation time

Three situations based on Eq.**(1)** can be defined: No mixing, mixing and complete instantaneous mixing.

Table 2: Possible situations of treatment time

1: No mixing: $t_{circulation} = t_{minimal.treatment}$
- Fastest possible treatment time.

2: Mixing: $0 < t_{circulation} < t_{minimal.treatment}$
- Intermediate treatment time. Mixing occurs, but with an average delay of $t_{circulation}$

3: Complete instantaneous mixing: $t_{circulation} = 0$
- Slowest possible treatment time.

A series of experiments is done to verify the assumptions, to measure $t_{circulation}$ and to estimate Q. For measuring $t_{circulation}$, a drop of ink is added to the cavitation zone. The time until the first moment that partially mixed ink returns to the zone gives an approximate circulation time **(figure 3)**. Q is estimated using measured values of the jet speed. The jet speed is used as input for a CFD, from which Q is obtained. The CFD is verified by filmed observations **(figure 5), (table 3)**. When Q is found, $t_{minimal.treatment} = V/Q$. During the experiments, the sonotrode is run long enough to let the flow fully develop before measurements start. Other parameters like power, frequency and immersion depth of the sonotrode are also kept constant.

3. Results

Table 3: Observations made during experiment

1	The flow is fully developed.
2	There are no dead zones.
3	The flow next to the jet is upwards.
4	The flow under the sonotrode is a downward jet.
5	An eddy is present in the lower half of the volume.
6	There is a 'slow' zone in the upper corner.
7	All flow is turbulent

The measured jet speed seems independent of volume and varies between 0.7 – 1.3 m/s **(figure 2)**. The CFD gives, based on the jet speed, an average flow rate Q that is also independent of total volume.

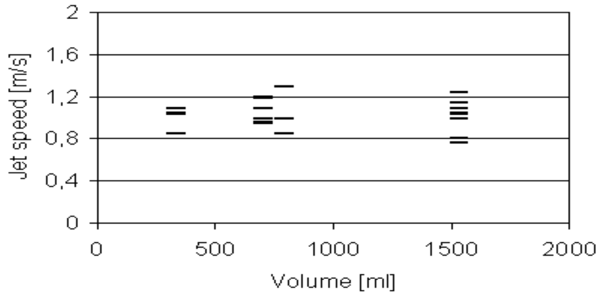

Figure 2: Measurements of jet speed

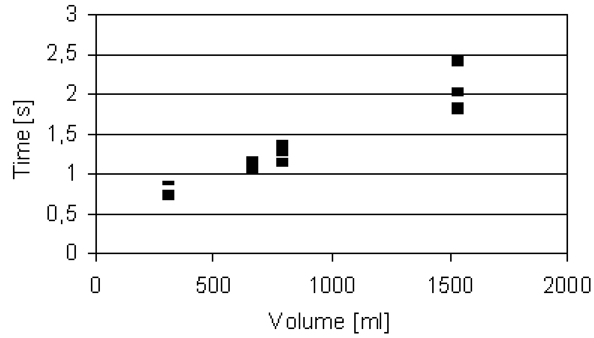

Figure 3: Measurements of $t_{circulation}$ for four different volumes

To compare treatment time per unit volume, the fraction $\tau = t_{circulation} / t_{minimal.treatment}$ is introduced. Values of τ close to unity resemble situation 1 **(table 2)**. Values close to zero resemble situation 3 **(table 2)**, thus higher values of τ, mean faster treatment times. τ is plotted in **figure 4**.

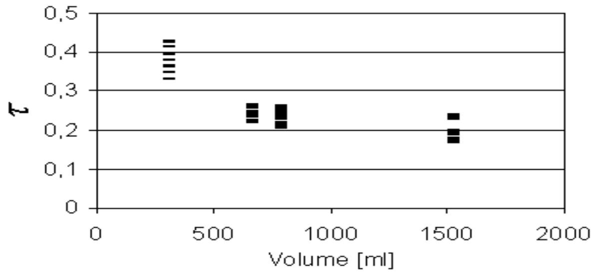

Figure 4: Calculations of τ for four different volumes

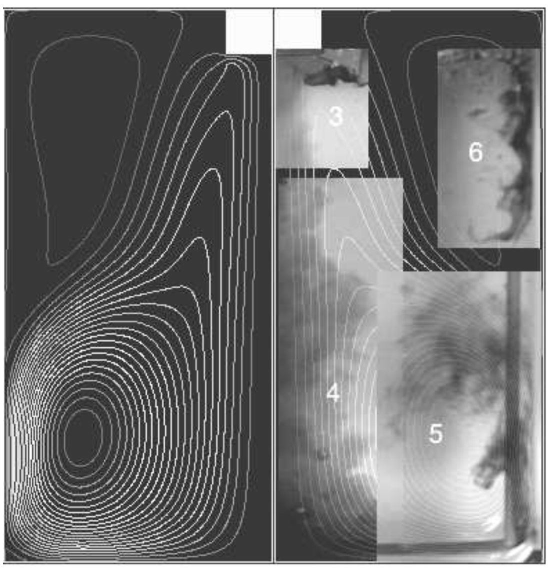

Figure 5: Left, CFD streamlines in a beaker (d=125 mm) Right, ink experiments. The numbers represent observations 3-6 from table 3

4. Discussion

Because the measurements of $t_{circulation}$ and the jet speed are done by manual processing of filmed images, they just give a rough estimation of reality. Assumptions 2 and 4 **(table 1)** are confirmed by observations 1 and 2 **(table 3)**. The CFD is verified with observations 3-6 from **table 3**.

Figure 6 gives graphs of Eq.**(1)** for situations 1-3 of **table 2**. Graph 2 **(figure 6)** follows from solving Eq.**(1)** with experimentally measured Q = 1.48e-4 m^3/s, V = 1.5e-3 m^3 and $t_{circulation}$ =2 s.

The treatment time for this situation is indicated by the **+** sign.

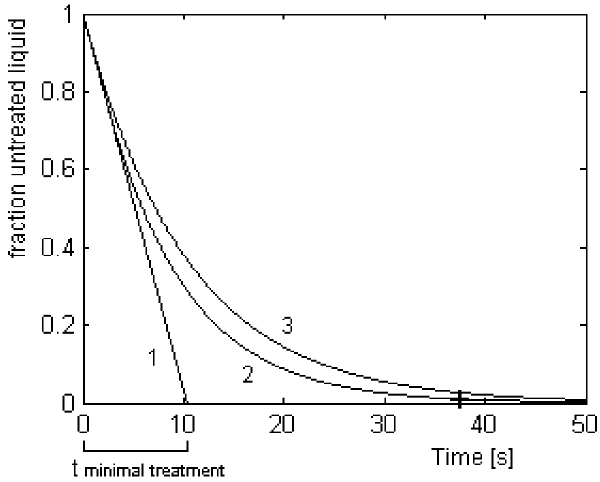

Figure 6: Development of fraction untreated liquid over time for situation 1-3 from table 2.

For cylindrical volumes with a diameter larger than 95mm, there seems to be a maximum of about 0.3 for τ **(figure 4)**. This would mean that the trajectory of the fraction untreated liquid is bound by graph 2 & 3 in **figure 6**. Because smaller τ make the trajectory shift towards graph 3, the following theory is formulated:

*The decay of the fraction of untreated liquid in a cylindrical volume with a diameter bigger than 95mm and a diameter/height ratio of 1, is bound by Eq. **(1)** with:*

- $t_{circulation} / t_{minimal.treatment} < 0.3$ (**figure 6**, graph 2)
- $t_{circulation} = 0$ (**figure 6**, graph 3)

5. Conclusion

Although the measurements contain a high degree of inaccuracy, more insight is gained in the cavitation-treatment time of liquid. Some of the most important results are:

- Insight is gained in the flow pattern and mixing.
- A theoretical model based on observations done during experiments gives an idea about the treatment time of liquid.
- Flow rates through cavitation zone seem independent of volume
- A simple CFD model shows streamlines alike observations made during experiments.

Further research is needed to test the theoretical model and enhance accuracy and understanding.

References

[1] G.I. Eskin, G. S. M. a. Y. P. P. (1995) Effect of Ultrasonic Processing of Molten Metal on Structure Formation and Improvement of Properties of Hight-Strength Al-Zn-Mg-Cu-Zr Alloys. Advanced Performance Materials 2, 43-50

[2] Ajay Kumar, T. K., Aniruddha B. Pandit, Jyeshtharaj B. Joshi (2006) Characterization of Flow Phenomena Induced by Ultrasonic Horn. Chemical Engineering Science 61, 7410-7420