Evaluation of sensors for inline viscosity measurement in gravure printing

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Motivation

- In gravure printing the viscosity of the ink has an important influence on print characteristics and quality.
- Inline viscosity measurement to keep the viscosity to a constant predefined level is essential.
- Falling sphere viscometers are the standard inline measurement devices, but need extra pipes and control equipment to operate them.
- Two types of vibrational viscometers recently came on the market for possible inline usage.

- For implementing inline viscosity measurement on our gravure press Bobst Rotomec MW 60 a test plan to choose the most suitable sensor for our purpose was conducted.
- For the examination of the different sensors, four tests have been designed:
  - precision,
  - behavior during the printing process,
  - temperature behavior in ink,
  - the behavior to external disturbing factors.
- Based on these tests recommendations were derived.

Viscosity sensors / viscometers

- Rotary viscometer
  Principle: Measurement of rotational speed of a rotating cylinder in a free fluid, which rotates with constant torque.
- Acoustic wave sensor:
  Principle: Measurement of needed energy for the oscillation of an electrostricitve plate moving perpendicular to and in contact with the fluid.
- Tuning fork sensor
  Principle: The sensor can be seen as a tuning fork with a flat profile at its end, which is electrically stimulated to an elliptical oscillation within a fluid with its resonant frequency. The surrounding medium impacts the resonant frequency of the tuning fork. As the fork profile is different in the two oscillation directions, the detuning in this two directions provides two distinct values, therefore enabling the calculation of both, dynamic viscosity and specific density.
- Efflux cup (offline reference)
  Principle: Measurement of the time of efflux of the fluid until the beam of fluid breaks into droplets. Specific for each type of cup (different volume and shape of cup and different size of efflux hole).

Viscosity measurement units

Viscosity is expressed in different measurement units.

- Dynamic viscosity η in Pa·s or (N·s)/m^2

- Kinematic viscosity ν in stokes or m^2/s
  Kinematic viscosity deducts from dynamic viscosity by dividing it by specific density

$$\upsilon = \frac{\eta}{\rho}$$

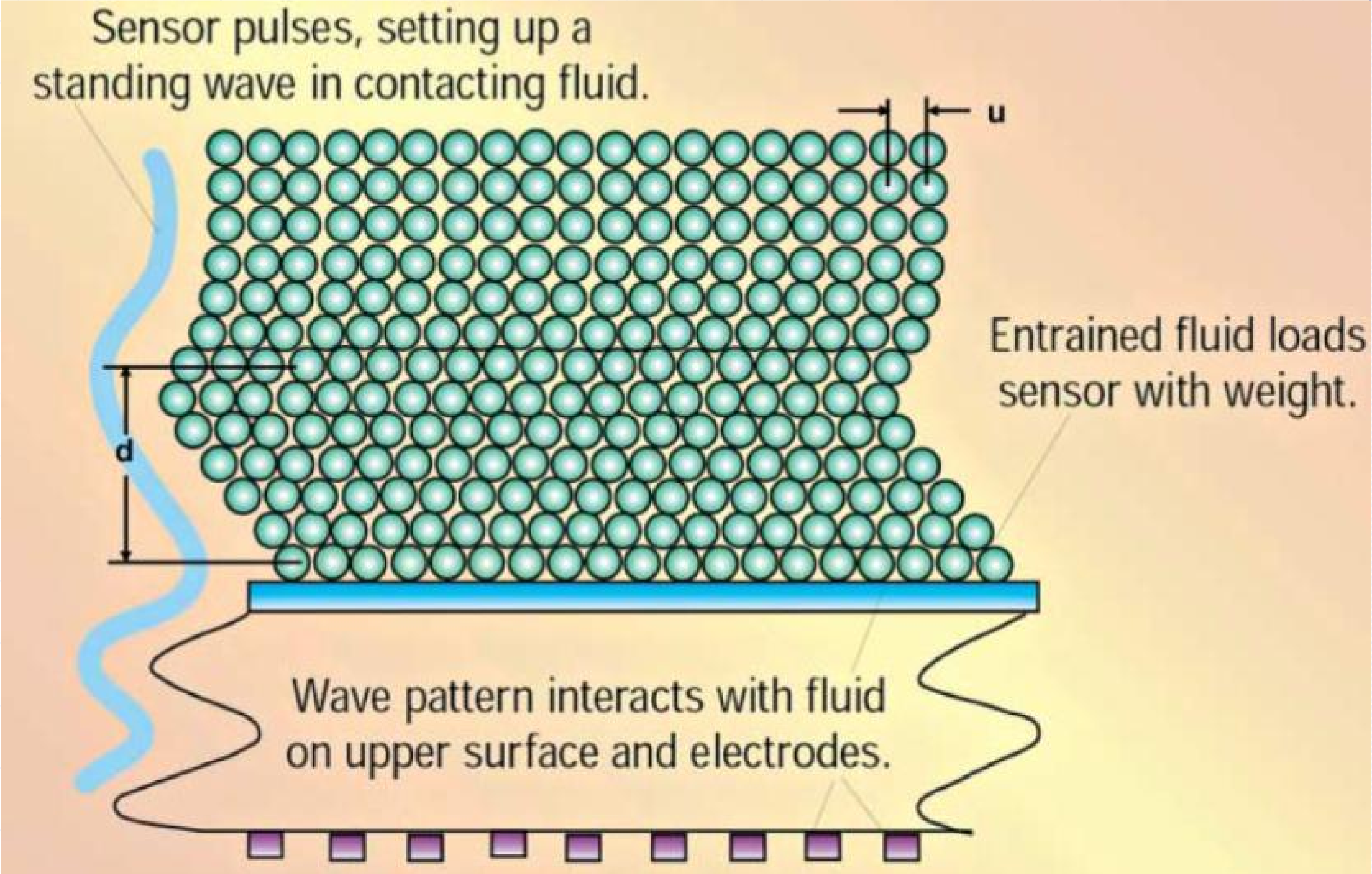
- Efflux cup seconds
  For Newtonian fluids a conversion table from kinematic viscosity to efflux cup seconds for every specific efflux cup can be made.

- Acoustic viscosity η_A in Pa·s · kg/m^3 or $kg^2/(m^4 \cdot s)$
  η_A is the product of dynamic viscosity and specific density

$$\eta_A = \eta \cdot \rho$$

Acoustic wave sensor

- An electrostricitve quartz plate oscillates perpendicular to the sensor surface with frequency ω and amplitude U.
- A certain layer of the fluid is hydrodynamically coupled with the sensor surface, its thickness d dependent on the viscosity.



Source: Special Bahnelektronik, 2007

Acoustic wave sensor

- Measurement is based on the acoustic impedance

$$Z = (\omega \cdot \rho \cdot \eta)^{1/2}$$

ω represents the angular frequency $\omega = 2 \cdot \pi \cdot f$,
ρ the specific density and
η the dynamic viscosity

- The penetration depth d of the wave into the fluid is dependent on the frequency, the viscosity and the specific density of the fluid:

$$d = \left(\frac{2 \cdot \eta}{\omega \cdot \rho}\right)^{\frac{1}{2}}$$

- The acoustic viscosity is measured through the power consumption of the quartz resonator that emits ultrasonic waves into the fluid to be measured to this depth *d.*

- The measured number (referred by the vendor as “acoustic viscosity”) is the product of the specific density and the dynamic viscosity and has the unit $g/cm^3 \cdot mPa \cdot s$

$$\eta_A = \frac{Z^2}{\omega} = \eta \cdot \rho$$

Experiments

1. Measurement accuracy of the solvent concentration

   Reproducibility of the viscosity measurements was tested with different inks representing the whole process range of solvent concentrations. The data obtained from this experiment were used to map the individual measurements to L% (quotient of solvent content of the ink to amount of basic ink).

2. Equipment capability study

Procedure	Purpose	Parameter
Procedure 1	Systematic error and repeatability	C_g, C_{gk}, t-Test, confidence intervals
Procedure 2	Repeatability, reproducibility (with operator influence)	%R&R
Procedure 3	Repeatability, reproducibility (without operator influence)	%R&R

Experiments

3. Temperature behavior in ink

   The change of viscosity as a function of temperature was measured.
   The aim was to examine the behavior of the different measuring instruments when handling ink which varies in temperature, e.g. cold ink at start up or heated up ink during running the printing process.

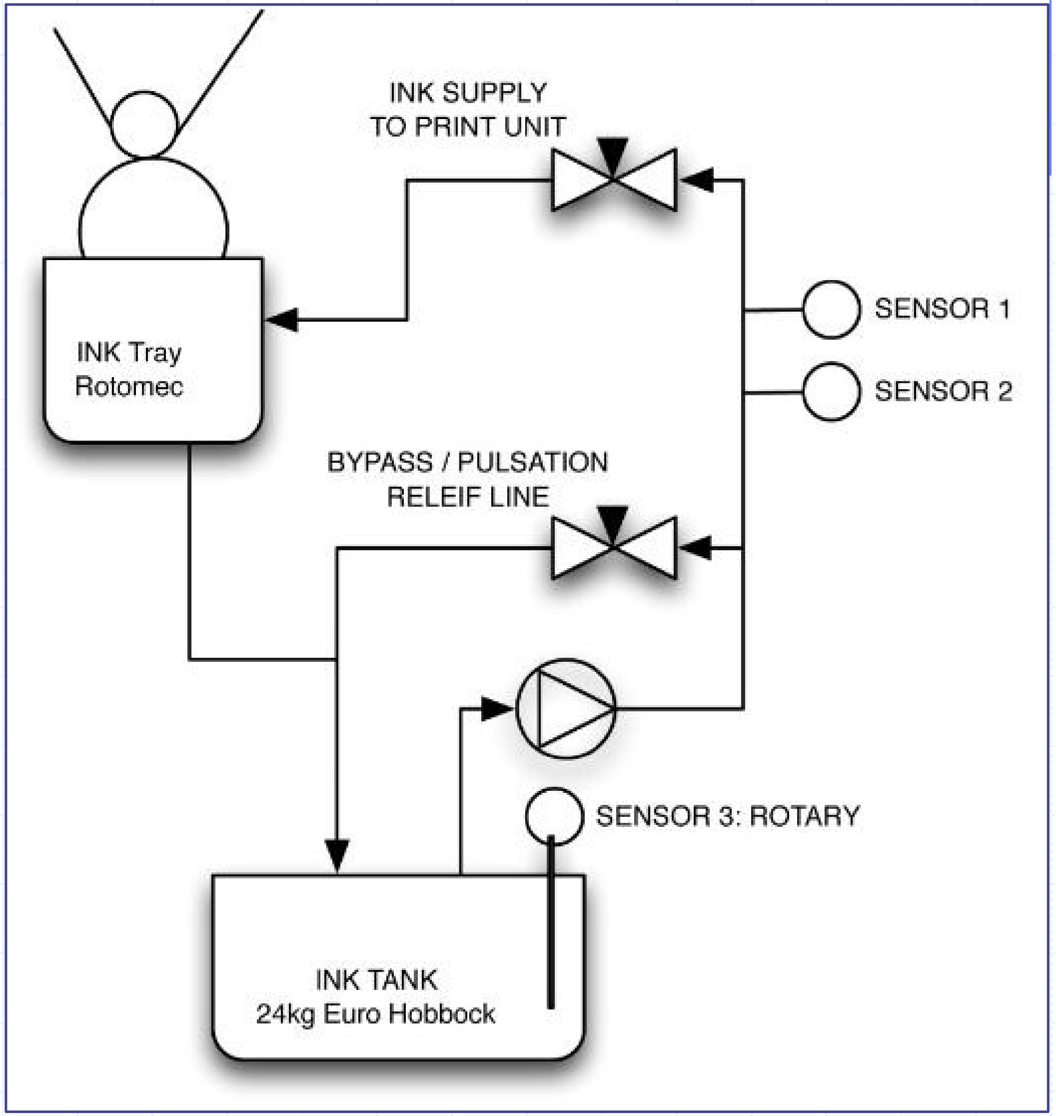
4. Influencing factors of the viscosity measurement in the printing process

   Typical influencing parameters to the measurement process were varied on press:
   - printing speed,
   - flow rate of ink within the inking system and
   - micro foaming extent.

   The aim of the experiment was to determine the viscosity measuring instrument with the best resilience within the process environment.

Experimental setup

- The viscosity measuring instruments were installed in the ink circulation of a Rotomec MW60 gravure printing press, which is driven by a double acting pneumatic pump.
- Sensor 1: Tuning fork viscometer
- Sensor 2: Acoustic wave viscometer
- Sensor 3: Rotary viscometer



Experimental setup

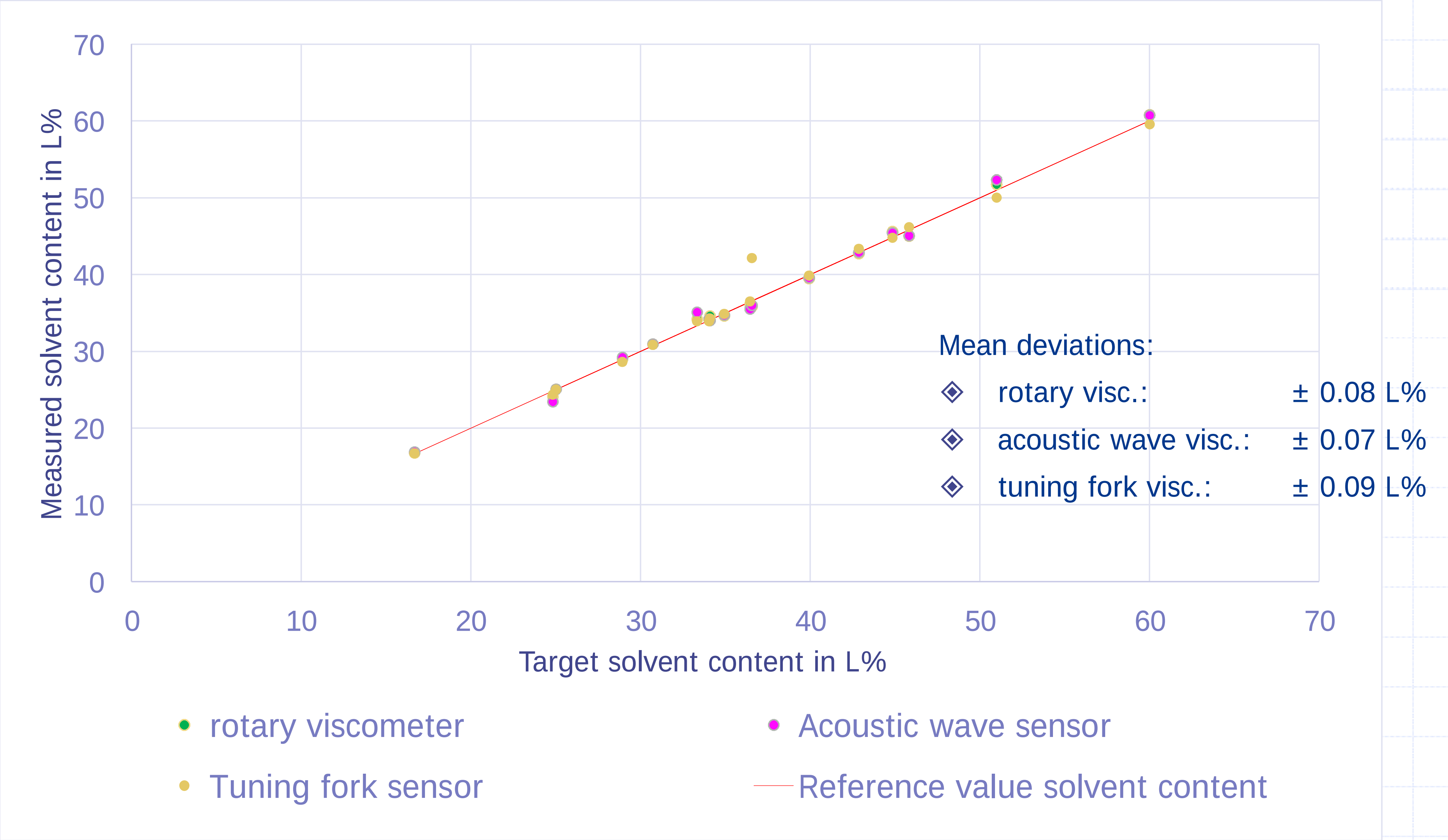
- Sensor 1: Tuning fork viscometer: dynamic viscosity
- Sensor 2: Acoustic wave viscometer: “acoustic” viscosity
- Sensor 3: Rotary viscometer: dynamic viscosity
- Efflux cup (Frikmar cup with 3 mm efflux opening): Seconds

- To normalize and compare between the three sensors and the efflux cup, the quotient of the amount of solvent additionally poured into the basic ink, delivered by the ink manufacturer, to the amount of the basic ink itself, was introduced, named L%.
- The dynamic viscosity is within the limits of our experiments indirect proportional to L%, so the graphs were referenced to L% or $\frac{1}{L\%}$:

$$y = \frac{a}{L\%} + b$$

y : value of viscosity measurement device and
a, b characteristic constants for each device and ink type.

Results: accuracy



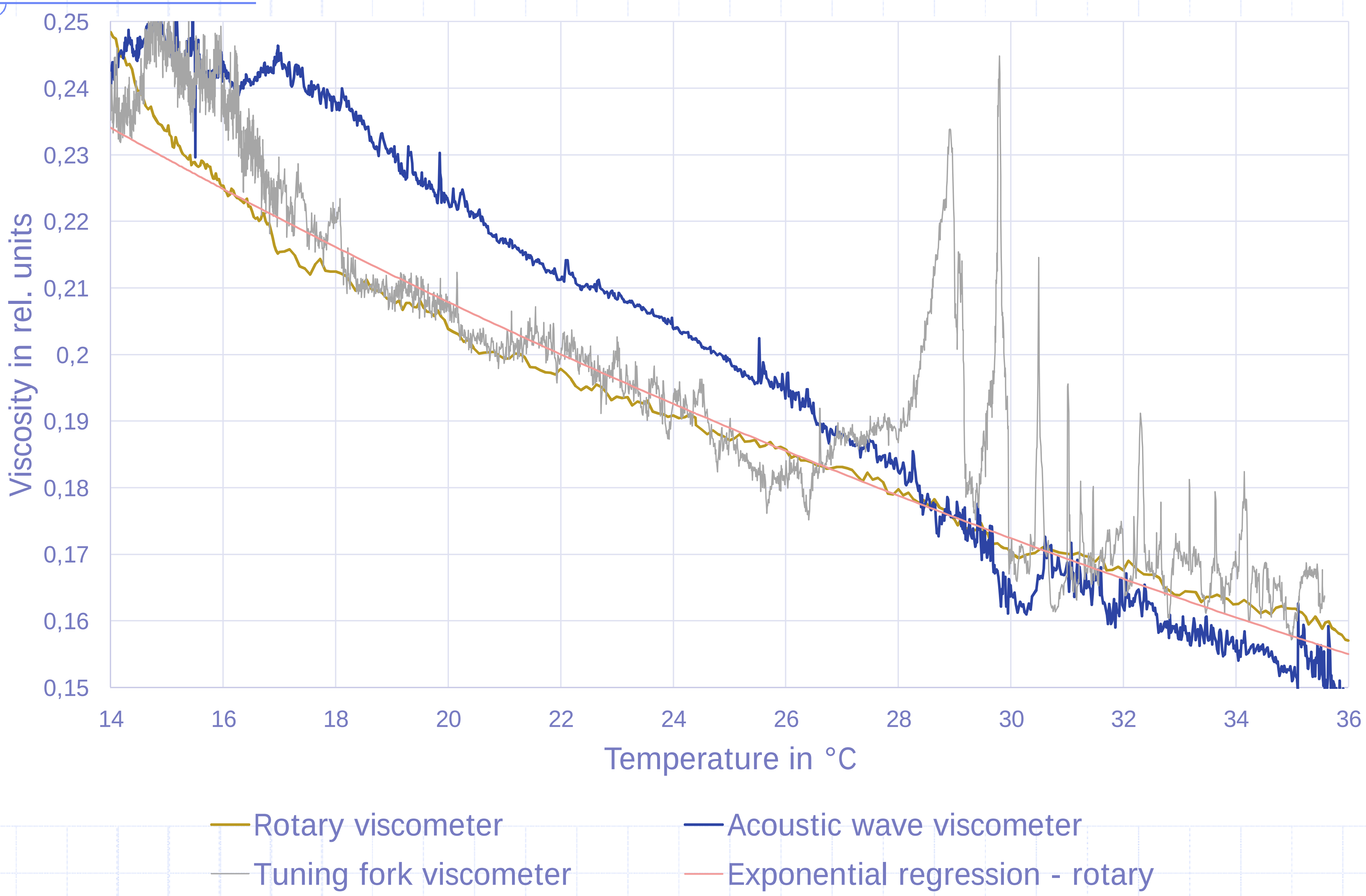
Equipment capability study

	Rotary viscometer in L%	Acoustic wave viscometer in L%	Tuning fork viscometer in L%
Basic size in L%	36.44	36.44	36.4
Tolerance in L%	4	4	4
Mean in L%	36.1	35.5	36.0
Standard deviation in L%	0.124	0.049	0.698
C_g (> 1,33 ok)	1.607	4.00	0.286
%R&R = %EV (<20% ok)	17.5	5.76	71.61

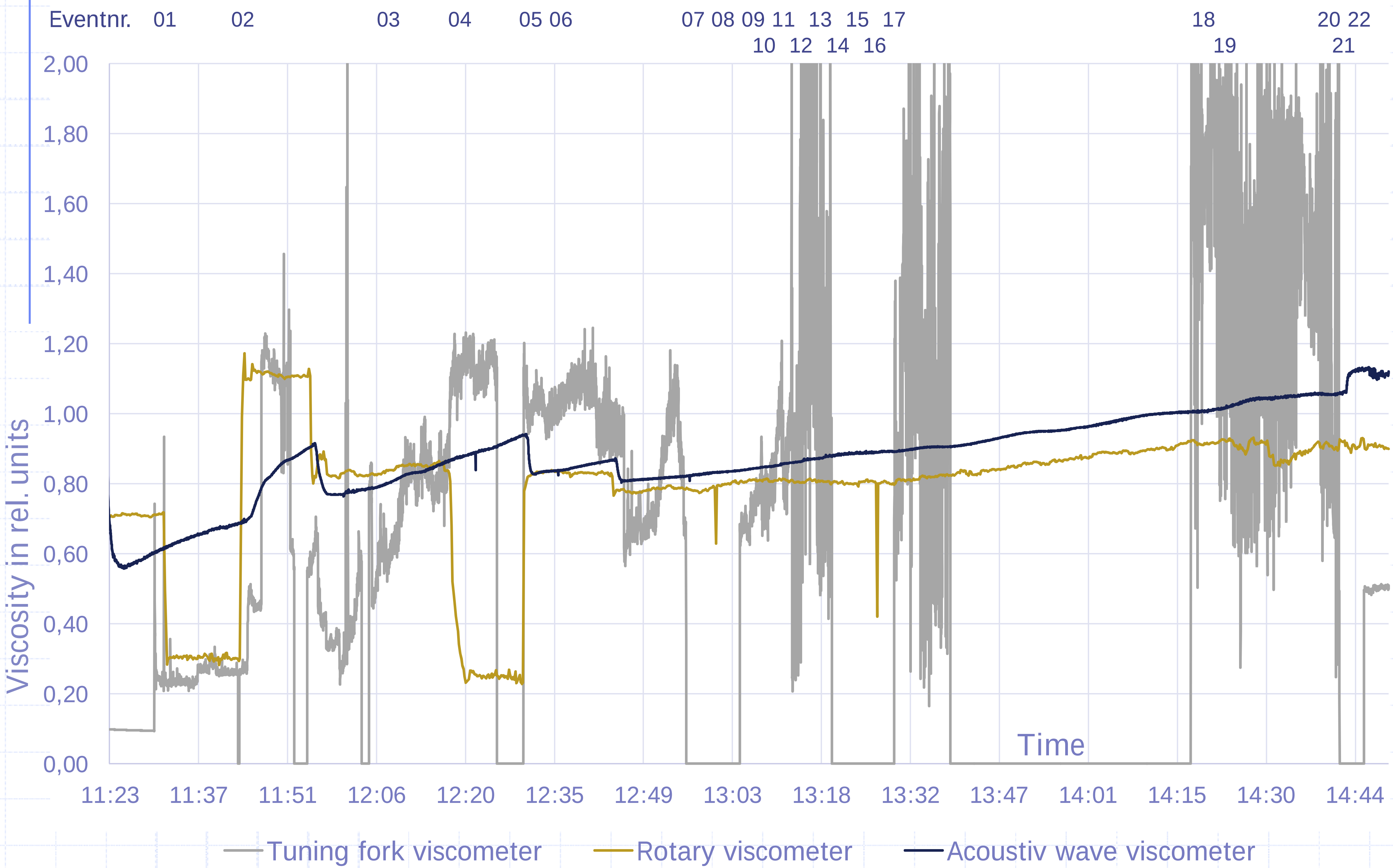
Testing fluid: Siegwerk NC 133-4 Black, 1 part basic ink, 1.5 parts extender, solvent ethanol, L%: 36.44.

Tolerance: +/- 1 second (3 mm DIN cup), which is a common number in order to avoid variations in print. This corresponds to a solvent content variation of +/- 2 L%, which leads to a tolerance of 4 L%.

Temperatur behaviour



Influencing factors to the viscosity measurement in the printing process



Influencing factors to the viscosity measurement in the printing process

Event Nr.	Time	Process Description
1	11:32	Rotary viscometer not surrounded with ink
2	11:44	Added ink
3	12:10	Printing speed: 180 m/min
4	12:15	Rotary viscometer not surrounded with ink
5	12:30	Added ink
6	12:35	Reduced printing speed: 60 m/min
7	12:54	Increased printing speed: 240 m/min
8	12:57	Reduced printing speed: 60 m/min
9	13:05	Bypass: off
10	13:08	Air throttling: open
11	13:11	Pump pressure: 3.5 bar / bypass: closed / air throttling: open
12	13:14	Pump pressure: 3.5 bar / bypass: closed / air throttling: open / Ink thr.: slightly open
13	13:18	Pump press.: 3.5 bar / bypass: closed / air throttling: open / ink throttling: half open
14	13:21	Pump press.: 3.5 bar / bypass: closed / air throttling: open / ink throttling: fully open
15	13:23	Pump press.: 2.2 bar / bypass: closed / air throttling: open / ink throttling: fully open
16	13:26	Pump press.: 2.2 bar / bypass: open / air throttling: open / ink throttling: fully open
17	13:29	Standard-setting as 13:05 clock
18	14:18	Printing speed: 300 m/min (without substrate)
19	14:24	Activation of stirrer
20	14:39	Aspiration of foam from the ink surface
21	14:42	Without ink tray
22	14:46	Aspiration of foam from the ink surface

Results

- The different levels of dilution are captured accurately by all measurement systems. The acoustic wave sensor delivers the smallest measurement variations over all levels of dilution.
- In the equipment capability study the acoustic wave sensor proved to be the most capable of the three viscometers.
  The rotary viscometer also showed sufficient capability.
  The tuning fork sensor could not prove its capability in the test set up used.
- The tuning fork sensor reacts very sensible to pump strokes of the pneumatic pump and to micro foam and therefore is without serious change of the setup, which we used, not suitable for an inline viscosity measurement system.
  Furthermore it was easily clogged with ink filaments, which occur sometimes in our inking system, and which wrapped around the oscillating rod and caused erroneous measurements.
- As the sensors use different measuring principles, they respond differently to temperature and solvent content variations of the ink, as in both cases viscosity and density changes are coupled.
  Therefore especially the acoustic wave viscometer has to be calibrated to correct for this effect.

Conclusion

- The tests showed that basically all viscometer are capable of gathering viscosity within the range of the used gravure inks.
- The rotary viscometer is capable and represents the current state of the art in the printing industry, but is difficult to integrate in our ink circulation system.
- The tuning fork viscometer cannot be used within our circulations lines due to its sensibility to pump strokes, foaming and clogging with ink filaments.
- The acoustic wave viscometer proofed to be much more insensitive to these effects and can be installed directly in the ink pipe.
- As it was the aim to find a system, which is accurate, minimize cleaning effort and can be installed on the press with minimal handling issues, the acoustic wave viscometer was selected.
- As it delivers the product of dynamic viscosity and specific density, its response characteristic is different than that of the other viscometers.
  This has to be taken into account and proper calibration is essential.

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