High-speed Mass Flow Measurement in Highly Viscous Adhesives by Constant Temperature Anemometry

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Abstract

State-of-the-art measurement cells suitable for highly viscous fluids (mainly gear-measuring cells or Coriolis measuring cell) show several disadvantages which interfere with the precision of a dosing process. These disadvantages are the significant pressure drop, the time gap between occurrence and detection of flow variations and the size and weight of those measurement cells.

This paper presents the development of a measuring cell which makes use of the thermal convection-based anemometry. This technique is widely used for the flow measurement of gas flow rates. The authors present a design with a digital PID controller which has been developed to convert a sensor for low viscous fluids to measure the flow rate of highly viscous adhesives. The experiments were carried out with a 1-component epoxy adhesive for structural bonding in automotive industries. This concept was verified with a semi-structural adhesive based on polyurethane.

Key words: Highly viscous adhesives/metering/high-speed flow measurement/constant temperature anemometry

1. Introduction

The precise, quick and correct mass flow measurement of highly viscous fluids is a challenging task due to the lack of suitable technologies which allow an accurate measurement by negligible pressure drops. For the exact dosing of high-viscosity fluids, a closed loop process is required which needs a feedback value to follow the set point. Most highly viscous fluids like adhesives for automobile industries, hot melts, slurries or pastes show non-Newtonian flow properties like shear thinning or thixotropy. Additionally those material characteristics depend largely upon the fluid temperature. This combination leads to the conclusion that the quality of the feedback signal, which is the measured flow rate, determines the quality of the overall dosing process.

The industrial standard for machinery dispensing adhesives with high precision is the use of a material supply plant and a closed loop metering plant. Typical pumps for the material supply are drum pumps: double acting piston pumps driven by an air motor which are able to pump the adhesive directly out of the drums1). The metering plant pumps with a better dynamic are: e.g. gear pumps or single acting piston pumps2). To realize a feedback to the closed loop controller, a measuring cell is needed to adjust the dosing pump according to the set point. Continuously working dispensing machines are typically finalized by a valve and a nozzle to control the shape of the bead. Fig. 1 shows a scheme of a setup for a 1-component dosing machine according to2).

The continuous flow rate measurement can be performed by volumetric measurements, e.g. gear or screw cells or gravimetric measurements like the coriolis mass flow meter3). Volumetric measurement cells are forced to move by the fluid which is pressed through the pipe system. The movement is detected and, due to
the fixed size of the tooth gap, a volume flow rate can be calculated. To gain a continuous flow rate signal a mean value needs to be built which causes long reaction times. Another disadvantage consists in high pressure drops of up to 100 bar. Coriolis mass flow meters make use of the Coriolis force: A thin tube, through which the fluid passes, is stimulated into an oscillation. A flowing mass leads to a distortion of the tube. While the response time is shorter compared to the gear cells, the pressure drop is still significant because of the small diameter of the oscillating pipes.

The objective of the following paragraphs is to show how convection-based anemometry can be used to gauge flow rate values in adhesive dosing processes.

2. Concept of thermal flow measurement

Thermal flow measurement is based on the forced heat flow from a warm corpus to a cooler fluid which streams along the corpus. While the heat flow by radiation can be disregarded and the heat conductance is constant, the convective flow of heat depends on the flow rate of the streaming fluid.

These effects can be used to determine the mass flow rate of fluids: A heat source with defined geometry needs to be placed within the fluid and either kept on a defined temperature (Constant Temperature Anemometry, CTA) or powered with a defined electrical current (Constant Current Anemometry, CCA). The first variant (CTA) needs a closed loop controller which measures the temperature on the sensor and controls the electrical heat-up current, which is used to calculate the mass flow rate. The second variant (CCA) is less complicated as regards the electrical circuit because it just needs a constant current source. The mass flow rate is calculated by the sensor temperature.

Fig. 2 illustrates both operating modes. The concept of constant temperature has the advantage that the sensor temperature does not vary and subsequently the thermal inertia of the sensor does not affect the measurement dynamic. For this reason the CTA concept is used in the following experiments. The CCA concept on the other side shows slower reactions to speed changes and there is a risk that the sensor will overheat during times with zero flow. This is especially critical when dosing hot curing adhesives.

3. Sensor platform

The thermal flow measurement is primarily used for very low viscous fluids like oxygen, air or water. In this field the requirement on the rigidity of the sensor
is quite low. Most of these sensors consist of a thin platinum wire with a diameter of ~100 μm, which are heater and temperature sensor in one. These constructions are much too weak to resist highly viscous fluids. Therefore a new sensor element had to be found which meets the requirements for this application. The result is a commercial element produced by Innovative Sensor Technologies. The element consists of two temperature-dependent resistors on a thin ceramic platform (0.3 mm thick). Fig. 3 shows the scheme of the platform.

The lower resistor (PT45) has a resistance of 45 ohm by 0 °C and is used as a heater and powered by current. The higher resistor (PT1200) has a resistance of 1200 ohm by 0 °C and is used to measure the sensor temperature.

Originally the Sensor is used in a Wheatstone bridge with both resistors in a different branch. A simple comparator regulates the heat current to keep the temperature in the tip constant. The PT1200 measures the temperature of the fluid.

This concept does not work for highly viscous fluids: First of all, the temperature gap between sensor and fluid needs to be higher (at least 25 °C above the adhesives temperature). This leads to a heat flow from PT45 to PT1200 through the ceramic. Furthermore, a heat flow occurs through the fluid when it lasts around the platform.

Fig. 4 shows the temperature distribution on the FS5L Sensor when it is heated up to about 15 °C above ambient temperature, measured with an infrared camera: While the tip temperature (Sp1) is about 34 °C, the temperature on the socket is still 31 °C which is just affected by the heat flow.

Another problem is the self-heating of highly filled adhesives which caused drifts when tested. In consequence an alternative controller setup had to be designed which decouples the reference temperature acquisition from the thermal conductance of the heater.

4. Measuring cell construction

The measuring cell consists of two FS5L elements. While the first one is used for being heated up and kept on a constant temperature above the fluid temperature, the second one is used to measure the fluid temperature permanently. Fig. 5 shows the concept with the PID controller which keeps the temperature of the actively heated sensor on a constant level.

The setpoint defines the temperature difference between the fluid and the sensor. Due to the permanent measurement of the fluid temperature it is possible to balance variations of the fluid temperature which would lead to inconsistent measurements. The mass flow rate is calculated by the voltage (based on Ohm’s law) which is needed to heat up the heater of the actively heated sensor.

Both sensing elements are included in a nozzle which is easy to introduce into a dosing machine that is capable of providing constant mass flow rates. Fig. 6 shows the nozzle. The actively heated element (B) is placed in the middle of the pipe to get the optimal flow stream.
5. Experimental results

To calculate the mass flow rate on account of the measured voltage to heat up the element A, a simplified Kings-Law function is used:

\[ \frac{U^2}{\Delta T} = B \cdot v^{0.25} \]

Where \( U \) is the voltage to heat up the sensor, \( \Delta T \) is the difference of the temperature in [K] between both elements, \( v \) is the average fluid speed and \( B \) is an offset factor.

The sensor behavior was examined for two 1-component adhesives: an epoxy-based adhesive for automotive bonding of structural parts with a viscosity of about 1000 Pas at application temperature and a density of approximately 1.3 kg/l. The second adhesive is a polyurethane-based adhesive for semi-structural applications like windshield bonding with a viscosity of about 200 Pas and a density of approximately 1.3 kg/l. Both adhesives show shear thinning behavior and a strong temperature depending viscosity. The viscosities were determined in oscillatory plate/plate measurement with a frequency of 5 Hz.

Fig. 7 shows a measuring result with both adhesives by different setpoint temperatures. The value \( B \) was mathematically fitted with the weighted least square method as 3.95 for the 25°C setpoint and 5.3 for the 40°C setpoint.

Fig. 7 shows that both adhesives have comparable properties. The graph also shows that the resolution of the measuring cell is better for slow flow rates and becomes less precise with higher flow rates. The local flow rate at the sensor is determined by the channel diameter and can be adjusted constructively.

With the described equation, it is possible to
calculate a mass flow rate by measuring the voltage. Fig. 8 shows a thermal flow measurement with the EP-Adhesive compared to a reference (in this case a Coriolis measuring cell).

The measurement in Fig. 8 shows a dosing process with different steps in mass flow rate from about 2 g/s to 11 g/s. The thermal measurement (red line) follows nicely the reference measurement (black line). By integrating both curves over time an absolute mass value was calculated in order to analyze the sensors accuracy. Over a time of about 15 minutes the difference between reference and thermal measurement was about 1 %. Unfortunately, the good accuracy of the measuring system of 1 % lasts only a limited period of time (a couple of days). The reason for this is likely to electromagnetic interference.

6. Conclusion and outlook

The results show that the concept of thermal flow measurement works for highly viscous fluids like industrially relevant adhesives. It is also shown that it is possible to measure different adhesives (PU and EP) with nearly the same calibration factors at the same setpoint temperatures. The quite low pressure drop (less than 1 bar) and the small size of the measuring cell give new possibilities for the design of adhesive measuring machinery and for the quality control of processes.

Unfortunately the measurement results are not as stable as required to manufacture a commercial system at this point of development. A much more reliable electronic circuit is necessary to get robust results which are not affected by electromagnetic distortions. This makes a frequent recalibration necessary.

These problems need to be sorted out in the next steps of development.

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