# On-line Monitoring of Viscous Properties of Anti-icing Fluid Based on Partial Least Squares Regression Modeling

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## Abstract

MSG Production is a company specializing in automated washing, de-icing, anti-icing and inspection of commercial passenger aircrafts. It is critically important that the viscosity of the anti-icing fluid is according to specifications. This study investigates if a combination of acoustic/vibrational measurements on the spraying nozzle of the system and multivariate regression modelling provides reliable viscosity estimates can be used for real time monitoring. The estimated viscosity based on independent test data show promising results for real time monitoring with a root mean square error of prediction of 278 [cP] within the valid range of the model which is 1900-8400 [cP].

*Keywords: partial least squares, multivariate regression, viscosity, anti-icing fluid, acoustic monitoring*

## 1 Introduction

MSG Production is a startup company, specializing in automated washing, de-icing, anti-icing and inspection of large commercial passenger/transport aircraft. The company has built a machine that automates the above-mentioned processes, by having an electric aircraft tug pulling it through the machine, much like a car in some automated commercial car-washes. Figure 1 shows the automated machine from MSG in operation applying anti-icing fluid to a passenger aircraft.

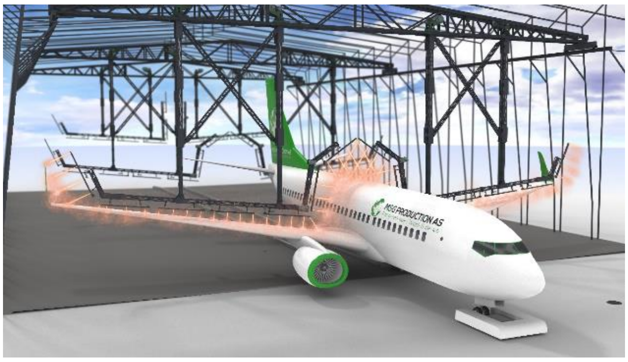

**Figure 1.** Anti-icing applied to a passenger aircraft using the new MSG technology.

The machine has devices for chemical fluids application hanging down from what is essentially traverse cranes overhead, with vertical telescopes holding a horizontal boom with multiple nozzles at a constant distance from the aircraft body and wings.

All control parameters for fluid application such as flow, pressure, temperature and fluid-quantity used are continuously monitored and documented.

Various parameters for washing, de-icing and anti-icing of any aircraft are described by the manufacturer, but there's also parameters related to de-icing and anti-icing that are dictated by the governing bodies of aviation, like SAE, FAA, IATA, GACA, ICAO etc. stating operational minimums for these procedures that are all related to aviation safety.

### 1.1 Anti-icing fluids

One of the objectives in this study is to investigate some of the physical (rheological) properties of the anti-icing fluid. The anti-icing fluid, of which there are several, (Type II, Type III and Type IV), is a polypropylene glycol, having a viscosity that is purposely thickened, and hence designed to make the fluid adhere to the aircraft wing during take-off and initial flight, until the aircrafts own anti-icing devices becomes effective enough to take over.

The anti-icing fluid is also known as a "pseudoplastic non-Newtonian" fluid also called shear-thinning fluid. This means that the lower the velocity gradient in the fluid, the higher the viscosity. This also imply that the viscosity can vary at different locations in the fluid dependent on the velocity field.

The anti-icing fluid is a polymer solution containing *large* polymer molecules. When the polymer is exposed to high mechanical stress (shear) the properties of the fluid can change, reducing the rheological properties of the fluid. This process is also called degradation of the polymer.

### 1.2 On-line monitoring of anti-icing viscosity

The main objective in this study is to assess if the vibrations occurring in the spraying nozzle of the system can be used for on-line real time monitoring of the viscosity of the fluid. Real time monitoring is preferred because the alternative approach involving manual sampling and off-line analysis using a rheometer is time consuming and does not provide continuous viscosity measurements.

The method which will be evaluated is called acoustic chemometrics (Halstensen *et al.*, 2010) The proposed method involves acoustic/vibrational measurements in the range 0-200kHz, digital signal processing (Fast Fourier Transform) and multivariate regression modelling based on Partial Least Squares Regression (PLS-R). The results can be used to investigate if the polymeric (viscous/rheological) properties of type II anti-icing fluid be degraded by exposing them to mechanical stress caused by the choice of technology in the anti-icing fluid spraying system.

An experimental test rig facility was used to simulate the mechanical stress that the anti-icing fluid is exposed to during application on the aircraft. The data acquired from these tests was used to train the PLS-R model. An independent data set was acquired for validation of the model in order to determine the model complexity (number of latent variables).

## 2 Materials and methods

A laboratory scale experimental test rig was designed and built to simulate the full-scale application process for anti-icing fluid. Viscosity was measured by taking samples from the transportation tank with fresh fluid from the manufacturer, and then again after being exposed to mechanical stress through the test rig.

Figure 2 shows the test rig piping and instrumentation diagram (P&ID). As can be seen in Figure 2 the pressure of the system is measured at various locations along the pipe to monitor the pressure loss. Temperature, pressure pertaining to the anti-icing fluid was recorded automatically during the tests. Five replicate samples were taken before and after being put through the test rig.

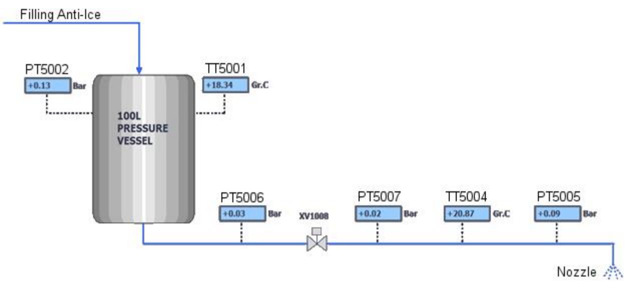


**Figure 2.** P&ID for the experimental test rig

The actual implementation of the test rig is shown in Figure 3. The rig has a pressure vessel containing test fluid, and a receiver tank to collect the fluid. The receiver tank holds the nozzle for fluid application. ID Ø-9.0 mm tubing connects the pressure vessel with the receiver tank and spray nozzle. The nozzle is a Veejet S.S.CO H1/4USS 8020 flat fan type, which in turn is used to apply anti-icing fluid to the aircraft. The pressure vessel was pressurized with air to 7.0 bar(g) for all of the tests. A pressure drop of approximately 1,8 bar from the pressure vessel to 5.2 bar(g) at the nozzle was observed. The pressure loss is affected by the design properties of the test rig and can be attributed partly to the hoses and partly to the rather restrictive inner diameter of the output valve from the pressure vessel.

**Figure 3.** Anti-icing nozzle test rig (top), nozzle with acoustic sensor (bottom).

An acoustic sensor (accelerometer) from Brüel & Kjær (BK 4518-002) was glued directly to the spraying nozzle as can be seen in Figure 3.

### 2.1 Anti-icing Safewing type II

The anti-icing fluid used was "Clariant SafeWing MP II Flight" polypropylene glycol which is a so-called type II anti-icing fluid. The viscosity of anti-icing fluid is a critically important property. Since this is a non-Newtonian fluid, the effect of strain to stress is rather complex. The anti-icing type II is as previously mentioned, a non-Newtonian fluid called pseudoplastic or shear-thinning fluid. The property characteristics of this fluid is such that the viscosity will decrease, as shear forces increases.

In this experiment, the viscosity for the anti-icing fluid was measured at various conditions. A Brookfield DV-III Rheometer was used for all the tests in accordance with ASTM D-2196-18 "Standard Test Methods for Rheological Properties of Non-Newtonian Materials by Rotational Viscountess" (ASTM D-2196-18 2018).

As per instructions given in ASTM D-2196-18, A 600 ml low form griffin beaker was filled with test solution. The instrument was zeroed, and the spindle was put into the solution. The rotation was set to desired value and the viscosity and temperature was recorded after 30 min.

## 2.2 Acoustic chemometrics

A survey of published literature concerning acoustic chemometrics shows that it has gained widespread use in industry. The publications span a broad variety of industrial applications demonstrating the potential of the method (Arvoh *et al.*, 2012,2012; Esbensen *et al.*, 1999; Halstensen *et al.*, 2006,2010; Ihunegbo *et al.*, 2012).

These applications include studies on liquids, particulate materials, and slurries. The advantages of acoustic chemometrics are:

- Non-invasive sensor technology
- Real time acoustic signal acquisition and processing
- Easy clamp-on/glue-on installation of acoustic sensors
- Several parameters of interest can be predicted from the same acoustic measurement

The main reason for choosing acoustic chemometrics is the on-line and non-invasive nature of this measurement approach which allows monitoring without disturbing the process. Furthermore, the total cost including both acoustic monitoring equipment and installation is relatively low compared to other on-line methods.

The sensor is an accelerometer which in this case is mounted directly onto the spraying nozzle of the anti-icing test rig. Figure 4 shows an overview of the most important signal processing steps involved in this method. In the first step shown in Figure 4 a) a time series of 4096 samples is recorded from the sensor. The time series is then multiplied with a Blackman Harris window (Ifeachor and Jervis 1993) shown in Figure 4 b) cancelling out the signal towards the ends of the series, the result is shown in Figure 4 c). This is important to prevent so-called spectral leakage in the final acoustic frequency spectrum.

The final step is the Discrete Fourier Transform which is used to transform the signal into frequency domain (Figure 4 d).

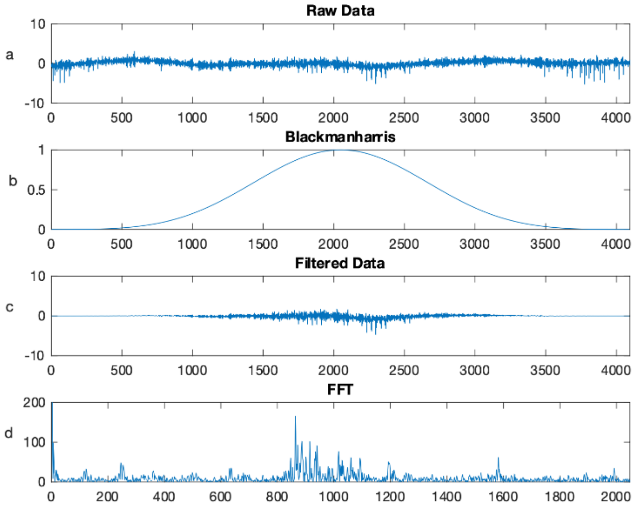


**Figure 4**. Acoustic chemometrics signal processing steps.

The Discrete Fourier transform (DFT) can be expressed as

$$X_k = \sum_{n=0}^{N-1} x_n e^{-i2\pi kn/N} \quad k = 0, \ldots, N-1 \qquad (1)$$

A more efficient implementation of the DFT is the Fast Fourier Transform (FFT) which in this work has been implemented in LabVIEW 2017 for fast real time calculation of the Fourier spectrum.

## 2.3 PLS-R

Partial Least Squares Regression is an empirical data driven modelling approach which is well explained in literature (Esbensen *et al.*, 2018; Martens and Næs, 1989) thus only a short introduction is given here.

PLS-R relies on representative training data for two variable blocks, often called X and Y respectively. In the present study the X data matrix contains the acoustic frequency spectra, and Y is a vector containing the viscosity of the anti-icing fluid.

The NIPALS algorithm is the most widely used algorithm in PLS regression. In this algorithm, the intention is to model both X and y simultaneously, make the error as small as possible and at the same time extract as much useful information from the X matrix in order to describe the y response variable. A simplified version of the NIPALS algorithm is presented below (Ergon, 2009). *A* is the optimal number of components in the model.

1. Let $X_0 = X$. For a = 1, 2,…, A perform steps 2 to 6
2. $w_a = X_{a-1}^T y / \|X_{a-1}^T y\|$ (with length 1)
3. $t_a = X_{a-1} w_a$
4. $q_a = y^T t_a (t_a^T t_a)^{-1}$
5. $p_a = X_{a-1}^T t_a (t_a^T t_a)^{-1}$
6. Compute the residual $X_a = X_{a-1} - t_a p_a^T$

$$X = T_w P^T W W^T + E \quad (2)$$
$$y = T_w q_w + f \quad (3)$$

where the score matrix $T_w = [t_1 \quad t_2 \cdots \quad t_A]$ is orthogonal, loadings matrix $P = [p_1 \quad p_2 \cdots \quad p_A]$, $q_w = [q_1 \quad q_2 \cdots \quad q_A]$ and the loading weight matrix $W = [w_1 \quad w_2 \cdots \quad w_A]$

The loading matrix, $P$, is calculated as

$$P = X^T T (T^T T)^{-1} \quad (4)$$

The prediction vector for $y = Xb + f$ corresponds to:

$$\hat{b} = W(W^T X^T X W)^{-1} W^T X^T y \quad (5)$$

The response vector $\hat{y} = X\hat{b}$ (6)

In evaluating the regression model, the root mean squared error of prediction RMSEP offset, slope and correlation coefficient are commonly used. Besides these, visual evaluation of the relevant score plots, loading weights plots, explained variance plots also provide useful information for calibrating and development of the prediction model.

The root mean squared error of prediction is calculated as:

$$\text{RMSEP} = \sqrt{\frac{\sum_{i=1}^{n}\left(\hat{y}_{\text{i,predicted}} - y_{\text{i,reference}}\right)^2}{n}} \quad (7)$$

## 3 Experimental

A controlled degradation test was performed in a pre-shearing rig where the purpose was to degrade the fluid to compare with the shear caused by the nozzle in the test rig. The fluid that was exposed to pre-shearing was mixed with factory fresh fluid and run through the test rig. A Brookfield DV-3 rheometer was used for all viscosity reference measurements.

In order to calibrate the PLS-R model it is important to vary the viscosity of the anti-icing fluid within a relevant range. Therefore, eleven different mixtures of factory fresh and pre-sheared fluid were prepared. The 11 fluids thus span a viscosity range of 1900 – 8400 [cP]. 10 liters of each viscosity was prepared and stored in plastic containers. All the eleven batches of anti-icing fluid mixtures were then run through the test rig and the corresponding acoustic signals from the accelerometer on the nozzle were recorded.

The signal from the accelerometer was amplified in a signal adaption module (SAM) developed by Applied Chemometrics Research Group at the University of South-Eastern Norway. The amplified signal was recorded using a data acquisition unit from National Instruments NI USB-6363 and a laptop computer.

An average of 50 spectra were used as basis for the final frequency spectra which was stored in the computer for further analysis based on multivariate regression modelling. The duration of each of the 11 tests was about 1 minute, and this resulted in 100 averaged frequency spectra for each viscosity. The temperature and pressure of the fluid in the tank and upstream of the nozzle were recorded during the tests to ensure comparable conditions for all the 11 viscosity tests. All the eleven batches of anti-icing fluid mixtures were then run through the test rig and the corresponding acoustic signals from the accelerometer on the nozzle were recorded.

## 4 Results & Discussion

Partial Least Squares Regression (PLS-R) was used to calibrate a multivariate model based on the acoustic data and the reference viscosity values. The reference viscosity values in each of the 11 mixtures were measured using the Brookfield DV-III Rheometer.

The acoustic data used to calibrate the PLS-R model was a 550x2048 matrix containing 550 frequency spectra. The calibration spectra were randomly selected from the total data matrix containing 1100 spectra. Each spectrum consisted of 2048 frequencies covering the frequency range 0-200 kHz.

### 4.1 PCA results

The resulting score plot t1-t2 for the first and second PLS-R component is shown in Figure 5.

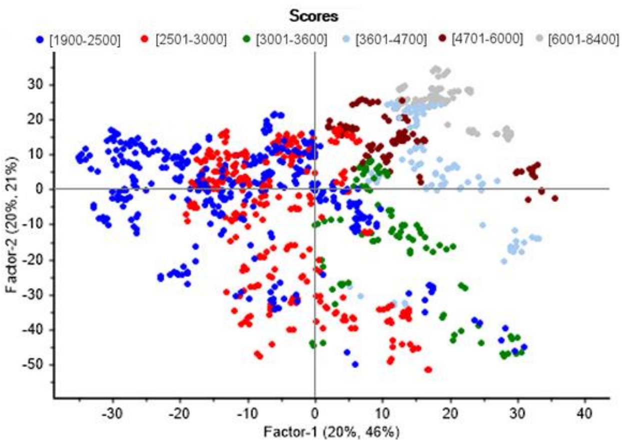


**Figure 5.** Score plot t1-t2, the viscosity of each sample is indicated by color according to the range given at the top of the plot.

The score plot shows how the acoustic spectra corresponding to the different viscosities relates to each other. Each acoustic spectrum is represented by a point with a color indicating the viscosity.

The score plot shows a promising trend in the data from low viscosity on the left side (blue) to the highest viscosity in the upper right corner (grey).

### 4.3 PLS-R prediction of viscosity

The PLS-R model was validated (Esbensen and Geladi, 2010) against a random selection of 550 spectra which is 50% of the total data set. Based on the test set validation the model complexity was determined using the residual validation variance plot shown in Figure 6. Five components were selected as optimal for the final prediction model.

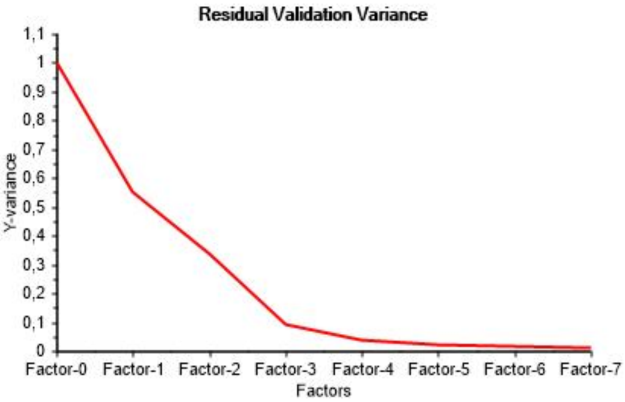


**Figure 6.** Residual validation variance.

The 550 predicted viscosities were plotted against the viscosities measured by the reference instrument and can be seen in Figure 7.

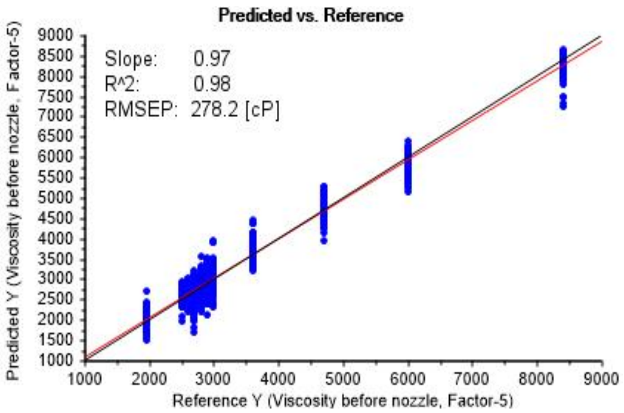


**Figure 7.** Predicted vs. Reference viscosity [cP]. The target line (black) and the regression line (red) are indicated.

The statistical parameters used to evaluate the prediction performance of the model are: slope=0.97, R2=0.98 and RMSEP=278 [cP].

The same results plotted in time can be seen in Figure 8. The green line is the reference viscosity and the red curve is the predicted viscosity.

The spread in the predicted values is mainly caused by air bubbles passing through the nozzle. Air bubbles in the anti-icing fluid is difficult to avoid, but if the fluid is left to settle for a significantly longer period than what was possible in this study the bubbles will surface, burst and disappear.

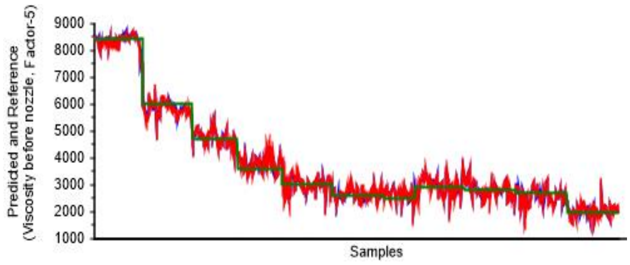


**Figure 8**. Predicted and Reference viscosity [cP].

The RMSEP=278 [cP] corresponds to 4.3% of the viscosity range 1900-8400. It can be observed that there are slightly lower prediction errors for the viscosity 8400 [cP]. The reason for this is probably that the 8400 [cP] fluid was taken directly from the tank as delivered from the manufacturer thus no mixing was required. It was also observed that the fluid with this viscosity contained significantly less air bubbles than the other batches of which all had been prepared as mixtures.

## 5 Conclusion

The main objective of this research study was to assess if acoustic measurements from the spraying nozzles in the system provide reliable predictions of the viscosity of anti-icing fluid. The results based on independent test data provided reliable predictions of the viscosity of the anti-icing fluid. It is concluded that the acoustic chemometric method which provided prediction performance indicated by the statistical parameters slope=0.97, $R^2$=0.98 and RMSEP=278 [cP] is promising for real-time monitoring of viscosity. However, long term testing is advised to assess the stability of the method in an industrial environment over time.

The advantage of the acoustic chemometric method will make it possible to monitor fluid viscosity during application to an aircraft in real-time. This is a significant improvement in risk assessment, mitigation and control.

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