Sensor positioning and thermal model for condition monitoring of pressure gas reservoirs in vehicles

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ABSTRACT

Passively acting safety relevant systems, e.g. automatic fire extinguishing systems or brakes, rely on the availability of compressed gases as acting medium and energy storage. Due to the safety relevance of these systems, it is necessary to monitor the condition of these elements continuously. However this task is difficult due to the partly abrupt changes in environmental temperature due to tunnel crossings and the interrelation of temperature and pressure in gases. As further the direct measurement of the gas temperature is difficult and costly, it is desirable to use external sensors to estimate the average gas temperature while at the same time avoiding false positives as not to reduce availability of the subsystems.

For this reason, the present paper analyses the behavior of a cylindrical pressure reservoir during changes in the environment temperature. The gas under consideration is Nitrogen under a pressure of approximately $200\,\mathrm{bar}$ at $15\,^{\circ}\mathrm{C}$. Aiming to identify a dynamical model of the gas temperature, different temperature profiles were simulated while measuring gas-pressure and temperatures in two locations within the gas reservoir as well as on the cylinder wall.

From the recorded data, a dynamical model is identified which expresses the relation between environmental and mean gas temperature. The estimated gas temperature from this system model is used to determine a reference pressure which can be compared to the observed pressure. In case of any mass flow from the reservoir, the error grows and an error can be triggered.

The model was developed using temperature curves resembling true operational curves simulated in a climatic chamber. The detection and classification behaviour was tested using computer simulations.

1. INTRODUCTION

1.1. Problem setting

The current FOGTEC fire fighting system does not use a constant condition monitoring system for the nitrogen cylinder. The nitrogen valve is only equipped with an analog pressure gauge to ensure that the pressure of the nitrogen is not below 160 bar. In case of the pressure going below this limit, a normally closed contact opens and causes a failure. The same failure appears also if the connection between the pressure gauge and the CPU gets broken.

The system is not able to distinguish between a failure which is caused by a gas leakage or a loss of pressure due to a sinking temperature. There is no option to define the size of a possible leakage or predict a lowering pressure without visual inspections. Due to this, every detected error leads to a malfunction of the fire fighting system and possibly to a stop of the vehicle or restrictions in traffic functions.

Especially in railway transportation, the occurrence of thermal shocks, caused by e.g. tunnel entrance and exit, plays a significant role in assessing the reliability of systems. However the problem at hand exhibits a non-negligible spatial extent of the gas reservoir as well as unknown heat transfer properties.

The interrelation of the demanding operational conditions, the economic pressure on the system and customer expectations of a reliable train service indicate that the proposed solution can be economically feasible and help to differentiate Fogtec systems further from its competitors.

1.2. Solution approach

The continuous monitoring of the condition of the pressure reservoir will lead to a classified failure detection. With the help of the defined condition of the cylinder at any time, the system is able to decide whether a loss of gas pressure is the result of a leakage or a sinking temperature. In case of the leakage a software can calculate its size and also the time until the fire fighting system is no longer in complete operation. The condition monitoring requires the to know the exact parameters of the gas. Measuring the gas pressure and the gas temperature at the same time is complicated. Replacing the analog pressure gauge by a digital temperature sensor and measuring the temperature at any place of the reservoir or the valve seems to be an easier solution.

2. CONDITION MONITORING

For a constant condition monitoring it is necessary to detect the pressure and the temperature of the gas. Because of the constant volume of the reservoir it might be possible to calculate a nominal gas pressure value out of the gas temperature. The main question is, if the measuring of the cylinder surface temperature is representative for the inner gas temperature and which sensor position is the most representative. To get an idea in which way the nitrogen mass in the reservoir effects the specific heat capacity it is helpful to look at a short calculation for a reservoir with a volume of $V_L = 20$ l.

The Mass of the empty nitrogen cylinder is $m_S = 22,4$ kg.

With a pressure of $p_N = 200$ bar and the ideal gas law, a constant volume, a constant mass and a constant amount of substance temperature the Volume of the expanded gas is:

$$p_{N,1} \cdot V_{N,1} = p_{N,2} \cdot V_{N,2} \Leftrightarrow V_{N,2} = V_{N,1} \cdot \frac{p_{N,1}}{p_{N,2}}$$

With $p_1 = 200\ bar$, $p_2 = 1\ bar$ and $V_1 = 20\ l = 0,02\ m^3$:

$$V_2 = 4000\ \mathrm{l}$$

The density of Nitrogen at $\vartheta_u = 20\ °C$ is $\rho_N = 1,15\ kg/m^3$. This leads to the mass:

$$m_N = \rho_N \cdot V_N = \rho_N = 1,15\ kg/m^3 \cdot 4\ m^3 = 4.6\ \mathrm{kg}$$

So the mass ratio is about 5:1.

This changes if heat capacity will be considered as well: The heat capacity of steel is $c_{steel} = 460\ \frac{J}{kg \cdot K}$. Nitrogen in gas form has a heat capacity of $c_N = 1000\ \frac{J}{kg \cdot K}$.

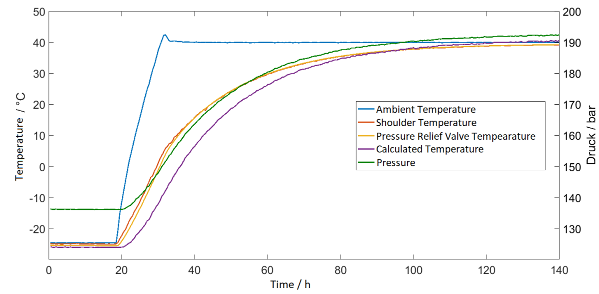

Figure 1. Results of scenario 2

The multiplikation of the heat capacity with the correlated masses goes to a heat capacity ratio of:

$$\frac{460\ \frac{J}{kg \cdot K} \cdot 22,4\ kg}{1000\ \frac{J}{kg \cdot K} \cdot 4,6\ kg} = \frac{10304}{4600} \approx 2$$

So the ratio is 2:1. This shows that the heat capacity of the nitrogen has a significant influence on the heat capacity of the whole system.

3. THERMAL MODEL AND SYSTEM DESIGN

To create a thermal model, the problem of the sensor positioning and its value has to be answered. Therefore a test reservoir is equipped with a pressure sensor at the valve and temperature sensors at different positions. Different scenarios show the behavior of the reservoir under different conditions.

The following scenarios have been simulated:

1. Temperature shock from room temperature (app. $21\ °C$) to $-25\ °C$
2. Temperature shock from $-25\ °C$ to $40\ °C$, as an example for passing a large tunnel in winter,
3. linear growing temperature from $10\ °C$ to $60\ °C$ in 5 h and
4. cooling from $60\ °C$ to $28\ °C$ in 14 h.

Figure 1 shows the result of the second scenario. At the point where the environment temperature begins to increase, the measured temperatures an the bottle shoulder and the nitrogen valve also begin to increase. The pressure and the calculated temperature follow after a short time delay.

The time delay is caused by the nitrogen's heat capacity and the necessary time for the thermal energy transport trough the steel into the nitrogen. To calculate the temperature value of the gas, a thermal model for the heat transfer is required. This model should be able to derive the gas temperature out of the measured temperature on the surface of the cylinder.

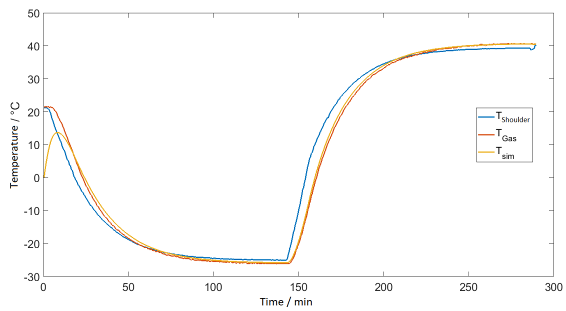

Figure 2. Calibration of thermal model

3.1. Thermal model

Following the data generation by help of the trial series, a model is created from the results of the test series, which can later be used for condition monitoring and leak detection. The model should be able to calculate a target pressure of the gas from any temperatures at a reference measuring point of the nitrogen cylinder. It is important to consider the time delay.

3.1.1. Gas temperature

First, a reference measuring point must be selected. The tests have shown that both a measuring point on the valve and one on the bottle shoulder are suitable. A measuring point on the bottle shoulder is advantageous because it can be implemented or installed very easily without technical changes of the reservoir or the valve.

3.1.2. Transfer function

The modeling is done using MATLAB's System Identification Toolbox providing the methods from (Ljung, 1999). This determines a transfer function from the data of a test series. To determine the transfer function, the values of the reference measuring point are transferred to the TFEST function on the input side. The output receives the values of the calculated gas temperature. The measurement data from scenarios 1 and 2 of the second series of experiments are used. The transfer function is first determined for the measuring point on the shoulder.

Figure 2 shows the temperature curves of the shoulder ($T_{Shoulder}$), the calculated gas temperature (T_{Gas}), and the simulated gas temperature (T_{sim}). The latter is the temperature curve generated by the transfer function. After a transient, this curve follows very well that of the gas temperature and differs significantly from $T_{Shoulder}$. The transient can be reduced by changing the starting value. Performing the same simulation with the valve measurement point results in a nearly identical course.

Table 1 shows the accuracies and errors of the transfer functions. It can be seen from this that the measuring point on

Table 1. Transfer function values

Measuring point	expected accuracy	expected error	mean square error
Shoulder	97.1 %	0.6359	0.6294
Valve	98.48 %	0.1748	0.173

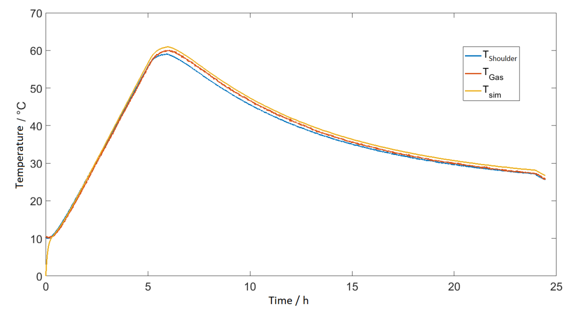

Figure 3. Simulation result of thermal model

the valve gives an even better result than the already good approximation by the measuring point on the shoulder. For simplicity, the reference point on the shoulder is preferred and selected for further viewing. The reference point can also be changed as desired afterwards.

The transfer function for the selected reference measurement point after the simulation is:

$$G(s) = \frac{0.003121}{s + 0.003021}$$

3.1.3. Validation of the transfer function

With the aid of the transfer function, the gas temperature is determined from the measured data at the shoulder of scenarios three and four. This is to see how the model deals with unknown data and how far they deviate from the actual, averaged gas temperature.

Diagram 3 shows not only the known graphs but also the simulated temperature. Again, a transient can be seen, but this is not so pronounced due to the slower change. This can be prevented as already mentioned by adding a defined starting value. It turns out that even a simple transfer function without starting value yields a good result. An even more precise function is also possible by changing some simulation parameters.

3.1.4. Gas pressure calculation

It is possible to determine the average gas temperature from a measured temperature on the outside of the pressure vessel. For a useful application the set value of the gas pressure must be determined based on this temperature. This is the set value pressure that the cylinder must have due to a certain surface temperature at a time. The rise of the linear function is $m = 0.8457\ \frac{bar}{°C}$.

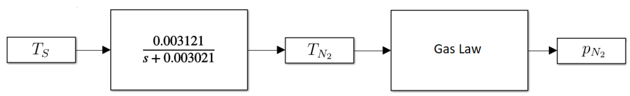

Figure 4. Model schematics

The scheme 4 clarifies the scheme of the system simulation. By means of the transfer function, the input signal T_S is transferred to T_S in T_{N_2} and then the output signal p_{N_2} is generated by a calculation using the gas law (Zierep, 1976).

However, this model only applies to the pressure vessel used here with the appropriate filling pressure. It can be transferred to other cases through further experiments. For this purpose, tests should be carried out with all cylinder sizes used. Different initial conditions can be interpolated after several test series. For this, the initial filling pressure of the cylinder must be known. The more different scenarios per pressure vessel are simulated, the more accurate the corresponding model becomes. Sufficiently good and many models also allowed for a transfer of the models to container sizes not considered by trial series.

3.2. System structure and possible use cases

With the help of the created model a possible monitoring system is designed. For this purpose, the existing model is supplemented so that a complete condition monitoring of a pressure vessel is possible.

The model needs as input the temperature of the shoulder. Therefore, this must be measured permanently by a temperature sensor. For the target - actual comparison, the current pressure of the container is required. For this purpose, the pressure gauge is replaced by a pressure sensor.

As already explained in Figure 4, the thermal model provides a target pressure which the pressure vessel should have due to the external conditions. This target pressure must now be set in relation to the actual pressure of the container. For this, it is advisable to subtract the current pressure p_a from the target pressure p_t. The result is then the deviation of the two values, which corresponds to the absolute error e.

Figure 5 shows the scheme of this error calculation. This calculated error must now be interpreted. For this purpose, a threshold is set, exceeding which means leakage. In addition, it must be ensured that a brief violation due to an error does not lead to a message. It should also be noted that the measured data may be contaminated with some noise. This must either be filtered out or taken into account when setting

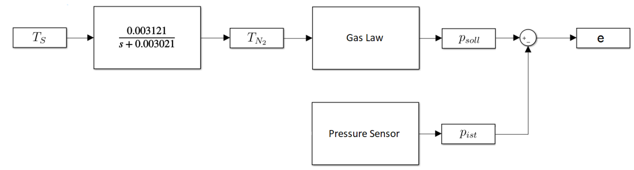

Figure 5. Error calculation Schematics

the threshold value. With the growth rate of the error, so its positive change over time and by knowing the pressure, the flow rate of the leak or a pressure loss can be determined, for example in bar per hour.

3.3. Simulation of particular use cases

In order to get a better impression of the function of the monitoring system, a possible scenario was simulated. An example of this is the passage through a warm tunnel in winter.

3.3.1. Temperature step at a tunnel passage

At this point a step response is displayed. Diagram 6 shows the behavior of the monitoring system during a sudden temperature jump. At time t_1 the temperature jumps from -10 C to 35 C. As already mentioned, such a scenario is modeled on a tunnel passage in winter. However, such a jump is only to be expected with an exposed container and even then only as a very rapidly rising temperature.

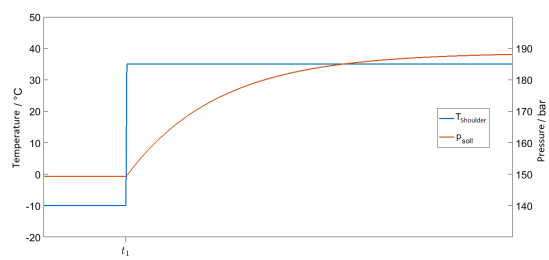

Figure 6. Simulation of temperature step response

3.3.2. Leakage

In order to simulate a leak after a temperature jump, the existing system has to be extended. Figure 7 shows the extended Scheme of the Simulation. To generate the pressure p_a, the pressure p_t is tapped and given a noise floor of $\hat{p}_R = 10\ mbar$. In addition, at a certain point in time, a constant, negative mass flow $\dot{M}$ is introduced. The resulting loss of pressure Δp_V is subtracted from the tapped pressure p_t. This simulated pressure p_a is then subtracted from the pressure p_t as before to obtain the deviation.

Figure 8 shows the time evolution of $T_{Shoulder}$, p_t, p_a and the error.

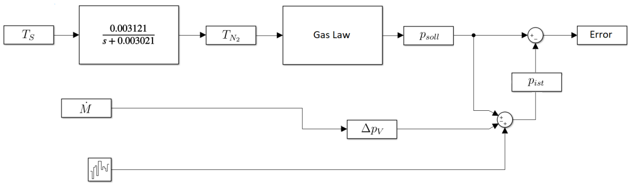

Figure 7. Extended scheme incorporating measurement noise

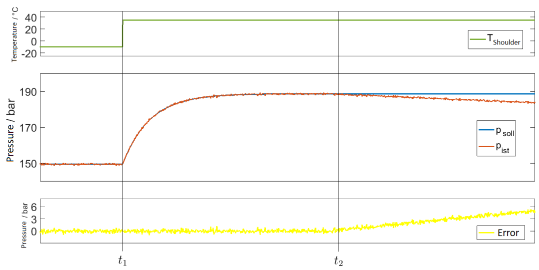

Figure 8. Leakage simulation

At the curve of p_a and especially at the error the introduced noise is clearly visible. At time t_1 another temperature jump takes place. After the resulting pressure equalization, the pressure loss due to the negative mass flow takes place at the time t_2. Until t_2 the two pressure curves are congruent. From the moment of pressure loss, the pressure p_a starts to decrease, causing the error curve to increase. Since this so-called error curve shows the time course of the absolute pressure drop, it is possible to determine the $\frac{\Delta p}{\Delta t}$ and thus calculate the absolute pressure loss. It is thus possible to predict after what time a critical situation for the functionality of the extinguishing system is to be expected.

4. CONCLUSION AND FURTHER WORK

The execution of the different test scenarios have shown the possibility to describe the exact condition of a pressure reservoir by measuring a temperature at any point of the cylinder while detection the gas pressure.

The model created for calculating a target pressure of the gas works to estimate the gas pressure reasonably well. Depending on the size of the $\frac{\Delta p}{\Delta t}$, it is possible derive different consequences for the system. These could, for example, prompt an immediate shutdown of the vehicle, a maintenance action as soon as possible or waiting for the next maintenance interval.

The development of these reactions requires further development steps and tests in real use. A potentially desirable development is the application of errors-in-variables methods (Söderström, 2007). Depending on these steps and future field tests, the application could be implemented in the CPU of the fire fighting system under consideration. Also, the connection a cloud infrastructure as in (Fumeo, Oneto, & Anguita, 2015) is desired for future developments.

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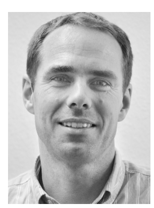
BIOGRAPHIES

Henrik Bücking was born in Oberhausen, Germany in 1986. He studied Mechanical Engenieering (RWTH Aachen) and graduated in Train Technologies (FH Aachen, B.Eng. 2018). During his study period he worked at IFS at RWTH Aachen and at Fogtec Brandschutz GmbH & Co. KG. After the graduation he starts working at Fogtec Brandschutz GmbH & Co. KG as a Test Engineer. He is member of the IMechE Railway Challenge Team of FH Aachen and member of Deutsche Maschinentechnische Gesellschaft (DMG).



Raphael Pfaff was born in Hagen, Germany in 1977. He pursued studies in Mechatronics (FH Bochum, Germany, Dipl.-Ing. (FH) 2006), Mathematics (FeU Hagen, BSc 2007) and Control Engineering (Coventry University, UK, MSc 2006, PhD 2013). He worked with Siemens and Faiveley Transport as System Engineer and Engineering Manager before receiving the call for his current position as Professor of Rail Vehicle Engineering at FH Aachen. His research interests include digitisation of railway rolling stock, reliability engineering and big data usage as well as wheel-rail contact modelling. He is member of the board of Interdisciplinary Railway Research Network (IfV Bahntechnik) and German Rail Engineering Society (DMG) as well as member of German Mathematical Society (DMV).

Roger Dirksmeier was born in Menden, Gemany in 1974. After his Education as Car Mechanical he studied Engineering Science (University for Applied Science, Cologne, 2001). He Worked as a Fire Safety Engineer at Deutsche Bahn AG and in different Management positions at FOGTEC Fire Protection, Cologne (Germany). Since 2016 he is Managing Director Rail Systems at FOGTEC Fire Protection.