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Modelling and Control of a Pressure and Temperature Test Chamber for Pure Mems Pressure Sensors

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Abstract

This paper presents the state space modelling of a temperature test chamber with 0.25 l volume that is tempered with a peltier device. A thermodynamic model of the test chamber is presented, giving different temperatures from heat gain, thermal loss network, incoming air temperature and airflow. Available temperature sensors are evaluated for their measurement uncertainty and an integrated solution is chosen. Control of the peltier device is discussed and based on the thermodynamic model a PI controller is chosen. A prototype is presented and model parameters are identified based on the step response. Static Accuracy is shown to be within 0.2 K with the PI controller.

Key words: peltier, temperature measurement, thermal network, temperature control

Calibrating pressure sensors for their characteristic curves under different temperatures is a well-known technique for sensor manufacturers. This is usually carried out with packaged sensors as well as with bare sensor dice, especially in the case of piezoresistive silicon sensors. Sensors are contacted either with prober needles or wire bonds and measured for their characteristics, e.g. base resistance, sensitivity, temperature coefficients, etc. The equipment used for generating temperature and pressure generally contains one or multiple climate chambers, which are additionally connected to a pressure controller. To achieve good stability of pressure and temperature control loops and change rates are engineered fairly slow. Despite the wide use of such test chambers, the involved thermodynamics and the control design of such systems has received little coverage in the literature. Therefore, this paper presents the design of a small test chamber with temperature and pressure control and focusses on important design decisions. The aim was to build a test chamber with a volume of 0.25 l, a temperature range of -40 °C to 150 °C and a pressure range from 0.1 to 1 MPa. This paper is structured as follows: First, a review of available devices and scientific literature is given. Section II discusses possible system architectures and the resulting state space equations. Section III gives a short overview of controller design and Section IV discusses possible sensors to close the control loop. Section IV presents a prototype of the system and results of first measurements. Finally, Section V concludes with a discussion of the results.

I Available Devices and literature

Industrial devices with temperature and pressure control are available in different sizes and sensor mountings, e.g. Kistler 6935A2 (Kistler, Winterthur, Switzerland) and PPS1210 (ICS Schneider Messtechnik, Bergfelde, Germany). Yet, a complete solution with tempered air and controlled pressure that can also be utilized below dew-point with dried air or nitrogen is not known to the authors.

In [1], a measurement setup including a climate cabinet and a pressure controller is described, yet the control algorithm is not mentioned. State space modelling of a peltier heater is described in [2], yet pressure is of no concern there. The modelling of peltier devices is also discussed in [3] and [4] in further detail.

II System architecture

An important decision when building a tempered measurement chamber applies to which heater/cooler to use and its placement. In the given case, a pressure-resistant chamber with 0.25 l volume and temperature range of -40 °C to 150 °C was desired. One possibility is to generate heat and cold from different chemical reactions and to apply them direct or with a heat exchanger to the test chamber. While chemical reactions are often very efficient, temperature accuracy with small thermal masses as in this work is only within ±2 K. Another often used combination, especially in commercial climate cabinets, is a resistive heater and a compressor for cooling. But again, compressors tend to be inaccurate with low air volumes. Therefore, in this work a peltier element is used. It enables cooling and heating with one device and also a fast turnaround from heating to cooling, which results in fast control.

Single-stage peltier elements only achieve temperature differences between hot and cold sides of ~70 K. Their lifetime also significally increases if one does not use the maximum temperature difference but stays ~20 K below it. Considering an ambient temperature of 20 °C, this is insufficient to the requirements. A solution are Two-stage peltier devices which pretemper the hot side (which is preferably at ambient temperature) of the first stage with a second peltier device, thereby reaching temperature differences of ~90 K. Therefore, a two-stage device is used in this application.

The following section discusses the placement of the peltier device. One option is to use it to temper the air in the test chamber. A second option is to use the test chamber as a heatspreader, temper it and let the test chamber temper the air contained within. In both cases, the general peltier device equations are needed. A peltier device generates a heatflow when a current is applied and an opposite heatflow if a reverse current is applied. Probably due to the reversal, the terms hot and cold side are not consistently used within the literature. Therefore, in this work the index *dev* denotes the side facing the heated/cooled device, while 2*amb* denotes the side that is meant to be kept at ambient temperature. With S being Seebeck-Coefficient (Volt/Kelvin), ϑ_{PE} absolute temperature of peltier device (Kelvin), I applied current (ampere) and q_{PE} resulting heat flow (Watt) one gets [3]

$$q_{PE} = S\vartheta_{PE}I$$

Additionally, the current through the electrical resistance R_{el} (Ohm) causes electrical or Joule heating losses q_{Joule} (Watt)

$$q_{Joule} = R_{el}I^2$$

The third important effect is the conductivity loss q_{Con} (Watt) from *dev* side with temperature ϑ_{dev} to 2*amb* side with temperature ϑ_{2amb}, limited by the thermal resistance $R_{th,PE}$ (Kelvin/Watt).

$$q_{Con} = \frac{\vartheta_{dev} - \vartheta_{2amb}}{R_{th,PE}}$$

This also holds for $\vartheta_{dev} < \vartheta_{amb}$, yielding negative q_{Con}. The aforementioned ϑ_{PE} is assumed to be

$$\vartheta_{PE} = \frac{\vartheta_{dev} + \vartheta_{2amb}}{2}$$

The heatflow on *dev* and 2*amb* side q_{dev} and q_{amb} then is

$$q_{dev} = q_{PE} + \frac{q_{Joule}}{2} - q_{Con}$$
$$q_{2amb} = -q_{PE} + \frac{q_{Joule}}{2} + q_{Con} \qquad \text{(I)}$$

Using electrical-thermal analogy [3], this can be modelled as two current sources, one supplying the *dev* side thermal network and the other supplying the 2*amb* side thermal network. 2*amb* side is typically equipped with a big cooling device, that can be modelled by a heat capacity in parallel with a resistor, see Fig. 1.

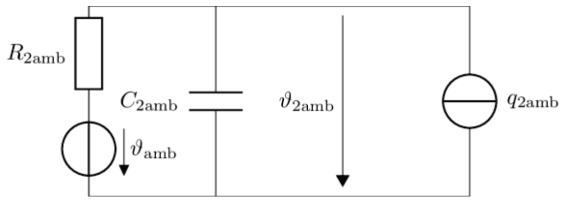

Fig. 1. Thermal Network of 2amb side.

The constituting equations for thermal capacities and resistors are $\vartheta = Rq$ and $\dot{\vartheta} = \frac{q}{C}$. Using these and Kirchhoff's Voltage and Current Laws results in the differential equation

$$\dot{\vartheta}_{2amb} = \frac{q_{2amb}}{C_{2amb}} - \frac{\vartheta_{2amb}}{R_{2amb}C_{2amb}} + \frac{\vartheta_{amb}}{R_{2amb}C_{2amb}} \qquad \text{(II)}$$

For state space modelling, one can conveniently choose ϑ_{2amb} as state variable and ϑ_{amb} and q_{2amb} as inputs.

Fig. 2 shows the system in the case of tempering air that is blown into the test chamber.

With c_P (Joule/(Kelvin*Kilogramm)) the specific heat capacity of the air, one can use the first law of thermodynamics to get

$$\dot{\vartheta}_{Air} = \frac{q_{dev}}{C_{Air}} - \frac{\vartheta_{Air} - \vartheta_{Wall}}{R_{W2i}C_{Air}} + \frac{c_P}{C_{Air}}\dot{m}_{in}\,\vartheta_{in} - \frac{c_P}{C_{Air}}\dot{m}_{out}\,\vartheta_{out}$$

$$\dot{\vartheta}_{Wall} = -\frac{\vartheta_{Wall} - \vartheta_{amb}}{R_{W2o}C_{Wall}}$$

The other possible mounting position of the peltier device is on the outside of the chamber, using the chamber as heat distribution device. This requires the test chamber to have good thermal conductivity. In this case, one can derive the equivalent circuit shown in Fig. 3.

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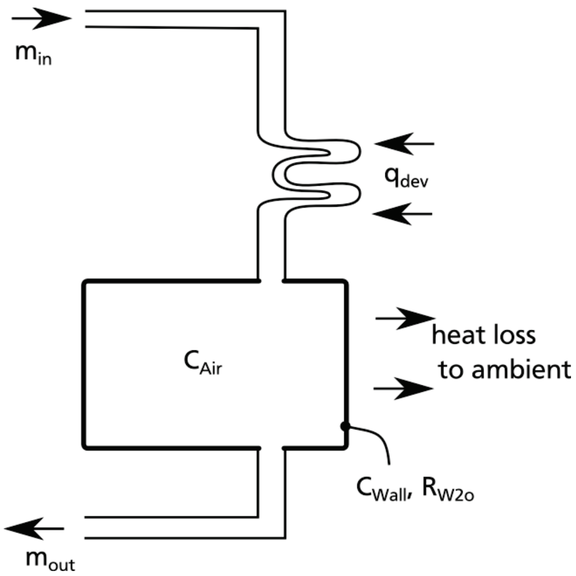

Fig. 2. Schematic view of system tempering air that is blown into the test chamber.

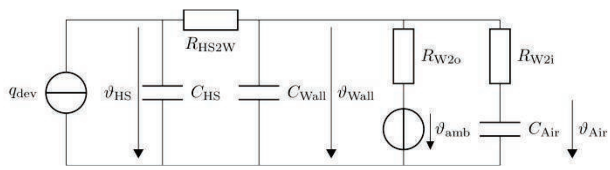

Fig. 3. Equivalent circuit of dev side when peltier device is attached to test chamber. It consists of a heatspreader (HS) at the peltier device which conducts heat to the test chamber wall (Wall) which will then go into ambient (W2o) and Air in the chamber (W2i) by convection.

The equivalent circuit is described by the following equations

$$\dot{\vartheta}_{Air} = -\frac{\vartheta_{Air} - \vartheta_{Wall}}{R_{W2i} C_{Air}}$$

$$\dot{\vartheta}_{Wall} = \frac{1}{C_{Wall}} \left[\frac{\vartheta_{HS}}{R_{HS2W}} + \frac{\vartheta_{amb}}{R_{W2o}} + \frac{\vartheta_{Air}}{R_{W2i}} - \vartheta_{Wall} \left(\frac{1}{R_{HS2W}} + \frac{1}{R_{W2o}} + \frac{1}{R_{W2i}} \right) \right] \quad \text{(III)}$$

$$\dot{\vartheta}_{HS} = \frac{q_{dev}}{C_{HS}} - \frac{\vartheta_{HS}}{C_{HS} R_{HS2W}} + \frac{\vartheta_{Wall}}{C_{HS} R_{HS2W}}$$

Using (I), (II) and (III) one can choose states $x(t)$ as

$$x(t) = \begin{pmatrix} \vartheta_{HS} \\ \vartheta_{Wall} \\ \vartheta_{Air} \\ \vartheta_{2amb} \end{pmatrix}$$

and inputs $u(t)$ as

$$u(t) = \begin{pmatrix} q_{2amb} \\ q_{dev} \\ \vartheta_{amb} \end{pmatrix}$$

and derive a state space model for the second mounting position with the initial conditions

$$x(t=0) = \begin{pmatrix} \vartheta_{amb} \\ \vartheta_{amb} \\ \vartheta_{amb} \\ \vartheta_{amb} \end{pmatrix}$$

III Controller Design

With the equations presented in the previous section, one has a state space model for the thermal network. Inputs are the heat flows from the peltier device. It would be beneficial to include the peltier device in the model, yielding only current as input instead of the heat flows. But this is not straightforward. The peltier device equation itself has no time dependency or time constant in it, so it yields arbitrary high frequency components when simulating it with time domain solvers. As the peltier effect itself contains the product of an input (I) and a state (ϑ_{PE}), it requires nonlinear controllers with the chosen states.

Still, a decent and easy controller can be found with the following consideration. Thermal time constants are fairly long compared to electrical. This means that the current through the peltier device can be adapted very quickly and will probably be at maximum value for long times. Therefore, a simple proportional gain controller will already deliver good results while changing temperature. For static accuracy, a small integral portion should be added, resulting in a PI controller. It is important, however, to avoid integral windup while current is at maximum value.

IV Temperature sensors

To close the feedback loop a temperature sensor is necessary. We evaluated different sensors in terms of their measurement uncertainty. Table 1 gives an overview of some commonly used principles and their uncertainty. Additionally, we evaluated temperature sensing IC for their measurement uncertainty. Details of this can be found in [5]. On this basis, we decided to use the SHT25 for its good accuracy and ease of use due to the I2C interface. It is worth mentioning that the HTU21D can be used as a 1:1 pin and software compatible replacement.

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Table 1. Overview of temperature sensing principles.

Sensor	Uncertainty	Reference
Platinum, e.g. Pt100	$0.15 + 0.002\,\lvert\vartheta\rvert$ (Class A)	DIN EN 60751
Thermocouples	around 1.5 K, depending on norm	DIN EN 60584
NTC, PTC	Around 1 K, nonlinear behavior	Various datasheets of manufacturers

V Prototype

The proposed test chamber setup was built using Aluminium. Fig. 4 shows the test chamber. This paper focusses on the second mounting position where the peltier device tempers the wall of the test chamber. A detailed description of the test chamber is available in [6].

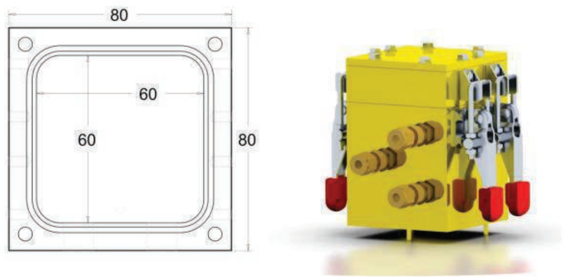

Fig. 4. The test chamber prototype. Left: Technical drawing. The inner chamber exhibits a depth of 70 mm. Right: CAD view of the test chamber.

Table 2. Measurement uncertainty of integrated temperature sensing IC with digital output.

Sensor	Measurement uncertainty with k=3
Honeywell HIH9131	1.05 K
Sensirion SHT25	0.87 K
Measurement Specialties HTU21D	2.1 K
Innovative Sensor Technology HYT271-S	1.74 K
GE Measurement ChipCap2	2.61 K

As a Two-Stage peltier element we chose 2QC-127-63-6.5 M (Quick-Ohm Küpper & Co. GmbH, Wuppertal, Germany). The 2amb side is fitted with commercial CPU heatsink with around 1 K/W thermal resistance. The peltier device is supplied with current by a HMP4040 laboratory power supply (HAMEG Instruments, Mainhausen, Germany) which in turn is controlled by MATLAB (Mathworks, Natick, Massachusetts, USA) via USB interface. Measurements are taken with the use of IOW56-DG USB to I2C Dongle (Code Mercenaries Hard- und Software, Schönefeld OT Großziethen, Germany). The controller loop with temperature acquisition is running in MATLAB with an update rate of up to 4 Hz.

For a first measurement, the step response was evaluated and the model parameters of section II were identified. Fig. 5 shows the results and Table 3 lists the identified parameters. With this parameters and the equations from section II the controller was tuned in simulation to a proportional gain of 3.6 A/K and an integral gain of 5e-3. With this controller a second experiment was conducted to test the static accuracy. Fig. 6 shows the results. It can be seen that most of the time the temperature is within 0.2 K of the setpoint.

Table 3. Identified parameters of the thermal equivalent circuit.

Parameter	Value
R_{2amb}	0.2 K/W
C_{2amb}	70 J/K
C_{HS}	10 J/K
R_{HS2W}	0.12 K/W
C_{Wall}	1100 J/K
R_{W2o}	1.4 K/W
R_{W2i}	2 K/W
C_{Air}	60 J/K

VI Summary and discussion

This paper describes important design decisions when building a small tempered test chamber. It focusses on the description of peltier devices and the state space modelling of the attached thermal network. The state space equations for two different mounting positions inside the system are shown and analysed. A glance at the controller design identifies a PI controller as an adequate solution. A simple prototype system is presented and tested. Equivalent Circuit and Controller parameters

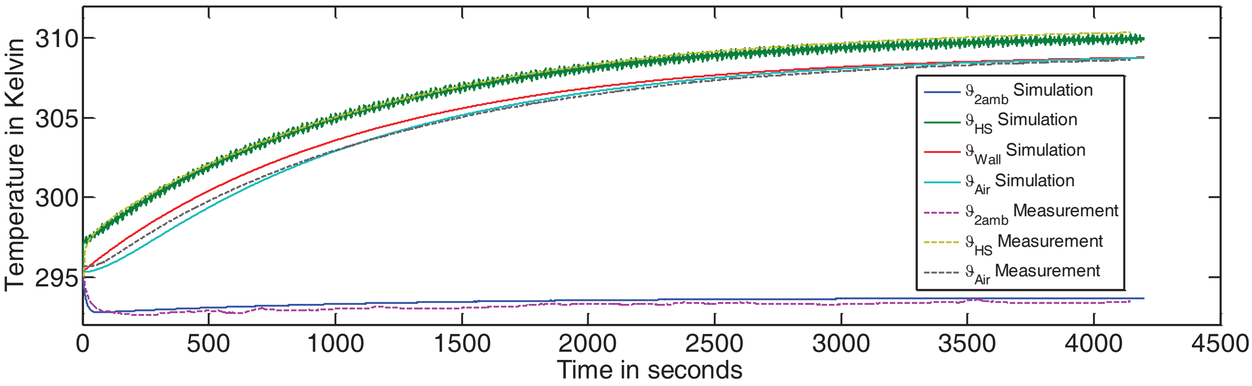

Fig. 5. Step response to a current of fixed current of 1 A. Controller is disabled.

are identified and show good results. Static accuracy is within 0.2 K.

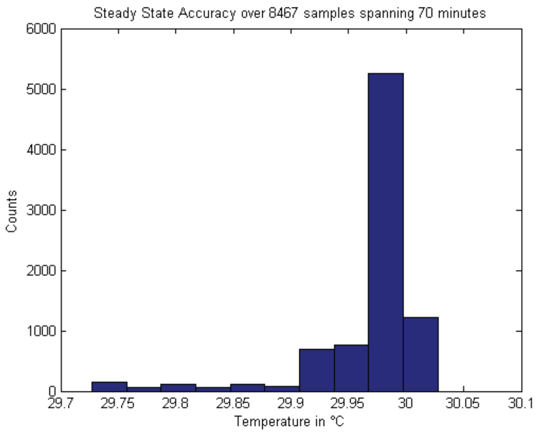

Fig. 6. Static Accuracy: Histogram of temperature with PI controller enabled. Set temperature was 30 °C, measured were 8467 samples within approx. 70 minutes (0.5 Hz sample rate).

Due to brevity reasons , this paper did not cover the pressure regulation. Nevertheless, the equations in section II already include air in and out flow and the pressure inside the chamber can be added as an observed state to the model. This will be published in future work.

The chosen PI controller works fine when using one peltier device, but faster response time can be achieved by coupling two peltier devices at the mentioned mounting positions. This also enables a simultaneous control of pressure and temperature not just by air flow but also by heat flow.

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