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Acoustic thermometer with a single waveguide

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***Abstract* – This paper presents implementation and testing of the acoustical thermometer with a single waveguide. Proposed design has a few specific advantages against other types of acoustic designs with waveguides, such as smaller size, better sensitivity and the same common sound path. The paper describes each advantage and tests used to determine their usefulness. Finally it shows how to deal with disadvantages of this design, such as weak return signals and possible coincidences of the return signals. The instrument was calibrated at ice point and then tested in oil bath from -30 °C to 120 °C. In steady states it has standard deviation of 0.050 °C with 66 independent readings per second. Stability of the bath is 10 mK and uncertainty of the reference thermometer is 0.003 °C.**

Keywords – sound, temperature, acoustic, PAT

I. INTRODUCTION

Acoustic thermometers are more known as primary thermometers [1] with very high accuracy, but are less useful for practical measurements, because they are too cumbersome. There were few proposals to construct similar kind of thermometers which would be similarly accurate, but more practical for everyday use. Those designs of practical acoustic thermometer were mainly within tube design [2], [3] or using measured medium as a waveguide [4]. Acoustic thermometers with waveguides are useful in harsh environments such as nuclear reactors [5] or other environments which could influence the measurement, for example high magnetic field. They are also useful where there is a need to measure the average temperature in large volume such as chemical reactors. They also benefit from low drift and cheap maintenance as they only need replacement of the gas inside to restore operation. Besides twin tube design which is most intuitive there are other designs such as joined twin tube design and single tube waveguide. Motivation to further explore single waveguide design is that other designs of acoustic thermometer have inherent flaws that are hard to overcome. For example, our early twin tube design tests had around 0.5 °C fluctuations in readings at room temperature, depending on environment influences such as room temperature, despite having good thermal connection between both tubes (copper wire wound around both tubes at the common sound path) and in the case of joined twin tube design it is hard to construct it in such a way that sound splits in both tubes evenly. Other motivation is that this design is more compact and has smaller measurement end as it is coiled into helix, compared to only bending it in the form of a letter U. The proposed design has a few specific advantages against other designs such as smaller size, better sensitivity and same common sound path. Unfortunately this design has also some disadvantages, such as: low amplitude of the return signal because of reflection and possible coincidences of the return signals. Section IV will explain how to deal with them.

The heart of problem with acoustical thermometers is determining the speed of sound. There are two main approaches, measuring acoustic resonance [6] or measuring time delay. This design measures a time delay or more precisely the time delay between the first and the second reflection of sound waves in the tube.

II. ACOUSTIC THERMOMETER

The scheme of the proposed design is shown in Fig. 1. With blue colour is marked the common sound path, which is tube with larger inner diameter. With green colour is marked the measurement end, which is tube with smaller inner diameter. This tube is twisted in helix with as small bending radius as possible for given tube material. Microphone is placed at the left end of the blue tube. At junction where tubes with different inner radius meet the first audio reflection is generated, the second reflection is generated from the end of measuring end where the tube is closed.

Fig. 1. Schematic diagram of the acoustical thermometer with single waveguide

A. Speed of sound

Speed of sound in the medium is mostly influenced by a medium itself and its temperature [7]. The relation is:

$$c_s = \sqrt{\frac{T\,\gamma\,R}{\bar{m}}} \quad (1)$$

where T is the temperature in Kelvin, R is the gas constant, γ is the ratio of specific heats C_p/C_v and $\overline{m}$ is the molar mass.

Equation 1 is valid in the free field, while in the narrow waveguide there is additional dependency on thermal and viscous boundary layers [8], which primarily affects at low frequencies (below 5 kHz).

B. Calculating temperature

In the proposed design the speed of sound is calculated with the time of flight method:

$$c_s = \frac{2l}{\tau} \quad (2)$$

where l is the length of tube with smaller inner radius and τ is measured transit time. The factor 2 is necessary as reflected sound waves travel same path twice. When inserted in the first equation it transforms to:

$$T = \frac{\overline{m}(2l)^2}{\gamma\,R} \cdot \frac{1}{\tau^2} \quad (3)$$

Equation 3 assumes that the first part is constant during temperature measurements, which is valid as instrument have slight overpressure in waveguide compared to the outside atmospheric pressure. The only parameter which is changing is the length of tube, but changes of length are compensated by the available thermal linear expansion data for used stainless steel (AISI 304).The constant part of equation 3 is determined by calibration at an ice point. This is needed because measurement of the length between microphone and sound reflective surfaces is too hard due to curvature of the tube.

C. Measuring of the transit time

In this design the microphone plays dual role, both as a microphone and as a speaker. The used microphone is Brüel & Kjær type 4189 [9] with custom preamplifier to allow using it as a speaker. For generating and capturing electric signals sound card EMU-0404 was used. The transit time measurement starts by generating a signal by a computer. Sound card generate electric signal to be transmitted by a microphone working in a speaker mode. Microphone then switches to a microphone mode to receive the reflected sound signals. The received signal then travel to a microphone preamplifier and a sound card. After that, microphone switches back to speaker mode. Computer starts another measurement after it calculates the transit time.

Excitation signal is a linear sweep with the frequency range from 5 kHz to 15 kHz. Both boundaries are determined for best results since low frequency sound waves have different speed and high frequency sound waves have higher attenuation when travelling through a tube. Signal length is limited by length of the smaller tube, which is around 2.5 ms in this design.

We use the pulse compression technique and matched filter to improve SNR and determine the transition time. Because the sound card sampling frequency is 192 kHz we had to up sample received signals by ratio 10 and use the quadratic fit when searching for the peaks in result of the matched filter. Thus, approximately 100 ns time delay resolution could be obtained.

III. RELATED RESULTS IN THE LITERATURE

Other attempts [1], [2], [3], [10] in construction of the acoustic thermometer with waveguides gave consistent results over wide temperature ranges and designs. Results show that uncertainty and deviation from model described in equation 3 are increasing with temperature. Results in range 30 °C to 50 °C are: 0.08 °C deviation from model and uncertainty of 0.005 °C. In the range up to 600 ° C the deviation from model rise up to 6 °C and the uncertainty to 0.5 °C. In the range up to 1000°C the deviation from model rise to 13°C and the uncertainty to1 °C.

Results in 1000 °C range are somewhat different from one design to other, but all indicate increasing deviation from model with temperature.

IV. INSTRUMENT DESIGN

Instrument is constructed from two main mechanical parts. The first is the measuring part and it is shown in Fig. 2.

Fig. 2. CAD image of measuring end of thermometer

Basically it is a tube bended in helix with one end closed and the other end straightened and left open. The open end is connected to the second part with another tube (shown in blue in figure 1), which has larger inner and outer diameter. The second part is cylindrical and it houses the microphone and the microphone preamplifier. This part also has the electric and the pneumatic connection to the outside. Insides of the helix, tube and microphone case are filled with air with slight overpressure to minimize the intrusion of surrounding air.

DC power supply, sound card, amplifier and control electronics are separated from the microphone box. Calculations and data storage are implemented on a personal computer.

A. Signal processing of received signal

Received signal is filtered and synchronized with the transmitted signal. After that, the matched filter is applied. Model used in the matched filter is the same as the transmitted signal, which is a linear sine sweep from 5 kHz to 15 kHz, but additionally filtered by the inverse frequency filter before matching. Parameters of the inverse filter are handpicked for best performance.

B. Length of pipes and their ratios

As mentioned in the introduction one major problem with this design is coincidences of the return signals. The proposed solution is to carefully choose the dimensions of tubes and ratios between them. In table 1 and 2 are displayed calculations for two optimal options. Length 1 is the length of the straight tube on figure 1 and length 2 is the length of the helix. Tables 1 and 2 show the sound path lengths for two different tube length ratios.

Table 1. Calculations for sound paths with length ratio 1:0.5

	length 1=1 m	length 2=0.5 m
First return	2 m	3 m
Second return	4 m	6 m
Third return	6 m	9 m

In this case the first reflected signal is from the first reflection, and the second from the second reflection.

Table 2. Calculations for sound paths with length ratio 1:1.5.

	length 1=1 m	length 2=1,5 m
First return	2 m	5 m
Second return	4 m	10 m
Third return	6 m	15 m

In the second casethefirst reflected signal is from thefirst reflection, second is thesecond return from the first reflection and thethird is from thesecond reflection.

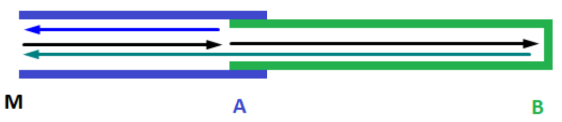

Fig. 3. Sound path inside the pipes. With letter M is marked the position of a microphone, with letter A is marked the position of first reflection and with letter B is marked the position of the second reflection.

In Fig. 3 are showed thesound paths in tubes with thelength ratios as calculated in table 2. Sound Start at M (microphone) and travels to the point A. Here path splits, half of thesound is reflected back to M (blue arrow) and half travels further to the point B. At point B all sound is reflected back to M.

Both cases are chosen so that signal return from the second reflection is between two returns from thefirst reflection to minimize theinfluence between both reflections. For this instrument it is better to choose second ratio with greater length of the measuring end to get better sensitivity. Total length is limited by the attenuation of returned signals and it depends on both radii of tubes, used microphone and the frequency of theused sound waves. Preliminary tests show that the maximum length for used tubes and microphone is 1.5 m. That is 0.6 m for the common path and 0.9 m for the measuring end.

V. EXPERIMENTAL SETUP

Before the main test could be performed few other, not temperature related, tests should be carried out in advance to determine thermometer parameters, such as microphone SNR and effect of switching the microphone preamplifier between themicrophone and thespeaker mode. The main test consists of two parts. The first is the thermometer calibration at an ice point to determine equation 3parameters. The second part is theactual temperature test in theoil bath from -30 °C to 120 °C. The used bath has temperature stability of 10 mK and the reference thermometer uncertainty is 0.003 °C.

One test cycle include 16 uniformly spaced steady states, each two hours long. In total there was 4 cycles which result in one week of testing. This test will show standard deviation and matching with model. It will also show presence of any hysteresis or drift.

VI. EXPERIMENTAL RESULTS

In Fig. 4 are plotted readings from the reference thermometer versus the acoustic thermometer. It can be seen that the line is almost linear with few bumps. These bumps are consequences of a larger time constant of the reference thermometer compared to the acoustic thermometer and they are only presented at the transient states.

From the Fig. 4 it is possible to see that the used model (Eq. 3) is good in range from -30 °C to 20 °C, but at higher temperatures there is a deviation which increases with the temperature. Further analysis showed that above 60 °C deviations from the model linearly increase with the temperature with a slope of 0.05 °C/°C.

Fig. 5 shows zoomed part of the measurements around 0 °C. With red are marked readings from the reference thermometer and with black colour are marked the readings from the acoustic thermometer. Readings from the acoustic thermometer are averaged to better show drift in the figures. Time 0 s is the start of experiments.

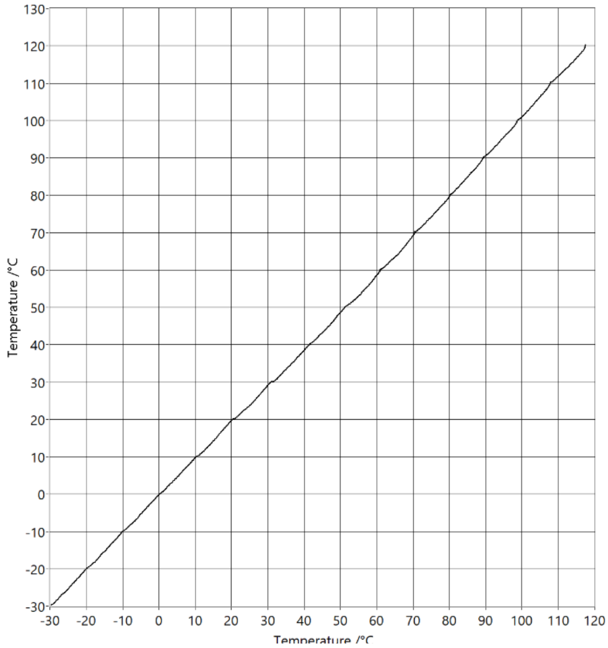

Fig. 4. Plot of reference thermometer temperature versus acoustic thermometer temperature readings.

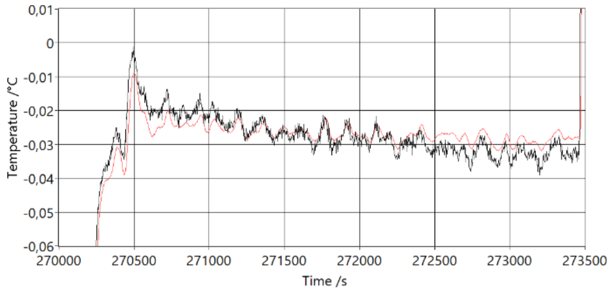

Fig. 5. Zoomed part of steady state around 0°C.

This particular steady state on the Fig 5 was 3.1 days after calibration and it shows that the thermometer doesn't have long term drift, but it can also be seen that it has some short term drift.

In Fig. 6 it is a zoomed part of the readings around 100 °C. Difference compared to the previous figure, is that the scale for acoustic thermometer is on right side of the graph. Difference between scales is 1.8 °C. This is done for easier comparison.

Fig. 6 show that at high temperatures we have similar short term drift as at lower temperatures and that at these higher temperatures model deviates from the measured results.

Test of SNR showed that the signal length of 2.5 ms is enough to get sufficient SNR after the pulse compression for temperature measurements. Switching between a microphone and a speaker mode did produce spikes in returned signal, but they were harmless due to a long pause, between one mode and another and they didn't influence the peak position after cross correlation

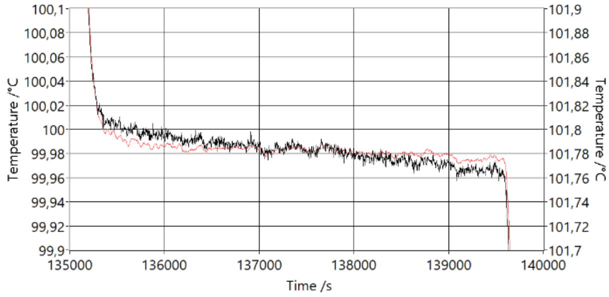

Fig. 6. Zoomed part of the steady state around 100 °C.

Heating the housing, but not the measuring end with a heat gun, didn't cause any temperature error, but did raise noise in the measurements while a heat gun was turned on.

VII. CONCLUSIONS

The proposed design offers new advantages against similar types of acoustic thermometers while retaining their benefits. The key change and advantage of this design is compact coiled measuring end since it enables this design to have a very high sensitivity in the small size. Other important changes are use of the sound frequencies, where sound speed is less dependent on its frequency and using the microphone also as the speaker improvesthemechanical stability of the system. Experimental results showed two problems with the current implementation. The first is short term drift and the second is deviation from the used model. Most probable cause of these two errors is use of an atmospheric air, with water vapour in it as the measuring gas in the PAT. After corrections for this deviation from the model, calculated standard deviation on 66 samples (1 second of measurement) at 100 °C was 70 mK with the oil bath running and 30 mK with the oil bath powered down.

VIII. FUTURE WORK

Using described algorithms and tube designs it is possible to achieve less than 2 °C temperature error at -30 °C to 120 °C range with a calibration at one temperature. With calibration at more reference temperatures or with applying the correction to the measured temperature it is possible to achieve temperature error below 0.4 °C at 120 °C.

Tests have shown three areas where the improvements are most needed. They are: using speaker with higher SPL, better acoustic insulation between outside and inside of the housing and filling the PAT acoustic tube with pure gas, e.g. argon or nitrogen. Other possibility for gas is xenon which has much lower speed of sound in it, 178 m/s compared to 319 m/s for argon and 349 m/s for nitrogen, at gas temperature 20 °C.

Increasing SPL and improving acoustic insulation would reduce the standard deviation of measurements and susceptibility to the outside noise. Changing gas inside of the housing and tubes would also reduce the short term drift and deviation from the model. Using xenon would also increase the sensitivity for almost factor of 2, compared to nitrogen or air.

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