Robust Gas Flow Metering Under Extreme Industrial Conditions

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In this thesis, a different method for creating acoustic pulses that can be used in the ultrasonic spectrum is proposed. The aim is to develop a robust and reliable system that uses ultrasonic techniques, such as transit time or sing-around, to measure gas flows in extreme environments. Extreme environments involve high temperatures, contaminating dust and sometimes high moisture content. The investigated method in this work utilizes electric spark discharges to generate acoustic pulses.

Studies of the gap discharge acoustic emitter were performed in two parts: environmental tests and studies of the transmitted sound. Environmental tests were performed at industrial sites to test the gap discharge emitter when exposed to heavy surface contamination and moderate temperatures. Studies of the transmitted sound were performed with a primary focus on the time stability of the emitted sound. Due to the nature of the spark discharge phenomena, there are inconsistencies in the transmitted acoustic pulse. When pulses are transmitted and received consecutively, their measured travel times will contain a time jitter relative to each other. This jitter is investigated and put into the perspective of a gas flow measurement situation. Acoustic pulses from the gas discharge emitter are shown to be strong enough to be used in large geometries of several meters. Additionally tests were performed in the industrial environments to determine if the acoustic pulses can be sent through large gas flow ducts and detected at the opposite side.

The tests show that the gap discharge transducer at the prototype stage performs well in a real industrial environment. The emitter continues to work when subjected to heavy contamination. The emitted sound is loud enough to be detected using standard piezo ceramic ultrasonic transducers when sent through large gas flows (air). If used in measurement situations that involve acoustic travel paths longer than around 1.5 meters and gas flows in the range of a few m/s or larger, this emitter can deliver sufficient accuracy.
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Part I
Flow measurements are performed everywhere around us, e.g., for gas stations, water supplies, district heating, and ventilation. Industry is, in many cases highly dependent upon reliable flow measurements to control and optimize production. In some cases, measuring a flow is difficult due to difficult conditions, which include high temperatures, the presence of contaminating dirt and dust particles, high moisture content, condensation, low gas pressures and large dimensions of several meters. Typical situations can be seen in Figure 1.1.

In industry, it is desirable to use flow meters without any moving parts because they generally require less maintenance. Flow meters without moving parts are dependent
upon some kind of sensing system to measure whatever is needed to estimate the flow. Dirt, moisture and heat, for example, will affect the sensors, and it is often the sensors that limit the specifications of the flow meter system. Another limitation is a very dirty environment, which might lead to heavy surface contamination, this may change geometric specifications that some flow meters rely on, such as differential pressure flow meters. Differential pressure meters, like venturi tubes, are commonly used under the described circumstances. Their biggest disadvantage is that they are cumbersome to use. For pipe diameters of several meters, they quickly become very large. Installing a venturi tube in an already existing process plant can be a very extensive and expensive project. Differential pressure meters are also dependent upon precise geometry to maintain their accuracy. In a contaminating environment, the need for maintenance increases, and so does the cost.

There are many places in industry today where it would be beneficial to measure gas flows, but it is not done due to difficult environmental conditions. Higher demands on production quality, efficiency and environmental requirements also increase the demand for additional and more accurate measurements. Typically identified capabilities that will make any new gas flow metering system competitive include the following:

- High temperatures, up to 1200°C
- Low gas pressures, around atmospheric pressure
- Accuracy of ±2% or better
- High moisture content sometimes condensing
- High dust contents and contaminating particles
- Long term service intervals
- Cost effective installation and startup

Therefore, if any new system is developed that allows flow measurements to be performed in these environments it should be possible to install it in already existing process plants. Ultrasonic flow meters have an advantage because they are relatively easy and cheap to install in already existing production sites. Ultrasonic flow measurement techniques are also non-intrusive, which means they do not affect the process unlike, for example, differential pressure meters. They are also capable of being configured in multipath solutions to achieve higher levels of accuracy.

1.1 Ultrasonic techniques in harsh environments

An ultrasonic flow meter is a non-intrusive system with no moving parts that utilizes acoustic waves in the ultrasonic frequency spectrum to estimate fluid flows. In a harsh environment, the weak points in an ultrasonic flow meter system are the transducers
because they are exposed. The piezoelectric transducer is the most commonly used currently. The piezoelectric transducer is limited at high temperatures. Piezoelectric materials have a specified Curie temperature. When exposed to temperatures at or above the specified temperature, their piezoelectric properties cease. They are also affected by dirty environments and difficult acoustic parameters. In gas, examples of difficult acoustic parameters include: high moisture content, low pressure and long travel paths for ultrasonic pulses.

1.2 Motivation for robust transducer technology

In order to develop ultrasonic gas flow metering systems for harsh environments, the transducer technology must be upgraded. Overall, it seems that the combination of high temperature durability and the ability to withstand aggressive environments is difficult to achieve. This makes it very interesting to investigate the possibilities of filling this empty space on the transducer utilization chart. If it is possible to develop new gas transducer technologies that can handle temperatures up to $1200^\circ\text{C}$, heavy contamination and non-optimal gas conditions, it would certainly be useful for applications that are not even considered today.

1.3 Thesis objective

The work in this thesis is focused on developing transducer technology that allows for ultrasonic gas flow measurements in extreme environments. Therefore, the following hypothesis is tested:

\emph{Ultrasonic gas flow measurement techniques can be applied in industrial applications that include extreme environments that include temperatures up to $1200^\circ\text{C}$ and the presence of contaminating dirt, dust, high moisture content, atmospheric pressures and large geometries.}

In order to test this hypothesis the following research questions can be raised:

1. \textbf{What kind of transducer technology can operate in a flow metering system under the given extreme conditions?}

2. \textbf{What performance will a flow meter system with this technology have?}

What kind of transducer technology can operate in a flow metering system under the given extreme conditions?

The only parts of the ultrasonic flow meter that are actually exposed to the fluid environment are the transducers. Thus, it is the transducers that must survive in the surrounding environment. Therefore, the most important question in order to prove the hypotheses must be the above.
What performance will a flow meter system with this technology have?

If a new technology is proposed, it is important to consider it from an end-user point of view. The new ideas may work well under controlled circumstances, but will it maintain its functionality when used in real applications? Parameters to investigate include: impact on accuracy, maintenance intervals, complexity, installation possibilities and price.

1.4 Thesis outline

This thesis consists of two parts. The first part provides an overview of current transducer technology, investigations of the gap discharge emitter and ultrasonic flow measurement techniques. The second part consists of the publications made within this work.
Chapter 2

The transducer

2.1 The ultrasonic transducer

An ultrasonic flow meter system utilizes the measurement of transit time of ultrasonic acoustic pulses in a flowing medium. By arranging the ultrasonic transducers such that pulses are sent both against and toward the flow direction and measuring the transit times in both directions, it is possible to calculate the average flow velocity in the sound path. To achieve this, the transducers must be able to produce and transfer acoustic energy into the flowing medium. This means that the transducer must be in contact with the medium. If the flow medium has one or several complicating properties, like dust, contaminating dirt, moisture, or high temperatures, this increases the demands on the transducer. In addition, if the flow medium consists of low pressure gas, it will be difficult for each emitted pulse to have enough acoustic energy. Adding industrial environments that contain very large geometries with travel paths of several meters increases the demand even further. To summarize, the transducers must be able to do the following:

- Withstand high temperatures
- Generate suitable high acoustic pulse energy
- Maintain functionality when heavily contaminated
- Detect pulses filtered through acoustically non-optimal gas conditions.

Therefore, available research and techniques and how they are expected to handle extreme environments are summarized.

2.1.1 Piezoelectric-based transducers

There are a number of different piezoelectric materials that can handle high temperatures.

Schmarje et al. [1] work with lithium niobate, LiNbO$_3$, composites for use in high temperature transducers. They mention that, although LiNbO$_3$ has a curie temperature,
The transducer

Figure 2.1: Example of piezoelectric ultrasonic transducer in steel housing. This is the 200-kHz transducer used as a receiver for the experiments in this work.

The Curie temperature, $T_c$, of about 1200°C, its operating temperature still lies around 650°C. According to Kazys et al. [2], this is due to the loss of oxygen from the material to the environment.

Kazys et al. [3, 4] have developed a high temperature (450°C) ultrasonic transducer that can be used for measurements in a liquid lead-bismuth alloy. They evaluated different piezoelectric materials and found out that bismuth-titanate is best suited for their needs. They report that bismuth-titanate has a $T_c$ of approximately 650°C and, thus, an operating temperature $T_o$ of approximately 550°C. The company Piezo-technologies [5], however, has a commercially available modified bismuth-titanate piezoelectric ceramic with a specified $T_c$ of 820°C with $T_o$ approximately 600°C. Ferroperm [6] also has a bismuth-titanate material available called pz46 with maximum operating temperatures of 500-550°C. Gallium orthophosphate is another high temperature candidate. Worsch et al. [7] have investigated this material. They report that the piezoelectric constant $d_{11}$ remains constant for temperatures greater than 700°C.

Another general problem that arises with high temperature piezoelectric transducers is crystal bonding. The crystal must be bonded to a housing in order to get support for proper functionality. At very high temperatures, it is difficult to find suitable bonding that will not compromise transducer functionality. The bonding materials must have both the correct acoustic properties and the capacity to maintain them with elevating temperatures.

2.1.2 Piezofilm-based transducers

Piezofilm is a very thin layer of piezoelectric material that is very flexible (Figure 2.2) and can be applied on different surface structures. Kobayashi and Ono et al. [9, 10, 11, 12, 13] have developed techniques to manufacture piezoelectric films from bismuth-titanate and lead-zirconate-titanate (PZT) materials and apply them on metallic substrates. They can be deposited on flat or curved surfaces, and some of them operate at very high temperatures above 500°C. Their frequency range is 5-30MHz. A more recent paper by Kobayashi et al. [14] reports LiNbO$_3$/PZT films deposited on a titanium substrate. These transducers were tested successfully in temperatures up to 700°C. However, their signal strength was seen to drop linearly with increasing temperature. At 550°C the signal
2.1. The ultrasonic transducer

2.1.3 Capacitive transducers

Another interesting technology includes capacitive ultrasonic techniques (CUTs). A CUT utilizes a membrane to produce ultrasonic pulses. A smaller variant of CUTs also exists, and they are called capacitive micro-machined ultrasonic transducers (CMUTs); an example of CMUTs is found in Figure 2.3. Kupnik and Schröder et al. [15, 16, 17, 18] are working to develop CUTs and CMUTs. They report successful measurements performed on 450°C pulsating gas flows from an automotive combustion engine. Tests in the laboratory environment show that the transducers should manage operate at temperatures up to 600°C. They have good sensitivity and operate with center frequencies in the range of 350-700 kHz. The –6-dB bandwidth for a CUT with a center frequency of 452 kHz is reported to be approximately 440 kHz.

2.1.4 Protection systems

In order to use available transducers under environmental conditions that exceed their recommended operation conditions, a type of protection system can be used. For ex-
ample, a buffer can be introduced between the transducer and the medium, which was attempted by Lynnworth et al. [19]. They report a buffer rod design that enables measurements in temperatures from -200°C to 600°C at frequencies of 0.1 to 1 MHz. Buffer rod solutions are commercially available under trademarks such as BWT and OKS [20].

High temperatures are not the sole source of problems for a transducer; in this work, environmental conditions that include dirt and moisture are also considered. Babic [21] presents a solution in which the piezoelectric element is separated from the medium by an air cavity and a membrane that transfers the ultrasonic pulse to the medium. However, any increased durability to raised temperatures is not discussed.

Another solution that is available on the market is SICKs active cooling, which uses an integrated air supply [22]. With this method, the transducer is specified to temperatures up to 450°C. It is also said to be suitable for high dust applications and aggressive gases.

2.1.5 Gap discharge emitters

Another method to acquire acoustic pulses that can be used in various applications is the use of a gap discharge device. An electric discharge that creates a spark between two electrodes gives rise to an intense and broad-banded acoustic pulse. Wyber [23] uses this property to create a broad-banded and intense acoustic pulse to investigate room coloration for acoustic tests. The acoustic properties of gap discharges have been investigated in a number of papers [24, 25, 26]. The intense pulses from a gap discharge are used in, for example, medical applications in so called lithotriptors. Lithotriptors use a focused and high-intensity acoustic pulse to break down urinary and biliary stones. This acoustic pulse can be generated by a spark discharge [27]. The emitted sound from electric discharges can also be used to detect dielectric breakdowns in oil-filled power transformers, according to Harrold et al. [28].

Using sound from a gap discharge for measurement purposes does not seem to be widely applied. Cooper et al. [29] use a spark discharge from an electrode to a surface to create acoustic waves in a test material. This is done in order to detect any defects, such as surface cracks. The pulse is detected using standard piezoelectric elements attached to the ends of the test material.

Gap discharge emitters have also been used in flow measurement applications described by Tretiakov and Beck [30, 31]. The device properties and performance are not will enumerated. The patent by Tretiakov [30] utilizes a gap discharge emitter together with piezoelectric transducers. This is a rather complicated device that is not necessarily suitable in rough environments.

2.2 Discussion available technologies

The focus in this work is to develop transducer technology that can handle both extreme temperatures and a harsh environment, which may include contaminating dirt and moisture. Regarding high temperatures, according to the review above, it seems that the current limit for continuous operation is 700°C. Although some piezo-materials
2.2. Discussion available technologies

have higher curie temperatures, they start to lose performance before reaching that point. They also have a tendency to begin to degrade when reaching their temperature limits, which makes them unsuitable for long operation periods. Many of the materials are also reported to lose significant amounts of sensitivity in their emitting/receiving abilities as the temperature rises, which is also a disadvantage.

Most of the above-mentioned transducer technologies also suffer from dirt deposits. A standard transducer depends on good acoustic matching of its emitting surface to the medium. When dirt deposits start to build up on this surface, acoustic energy losses occur. If the medium consists of a low pressure gas, like air at atmospheric pressure, the effect is even greater. This recalls for regular maintenance unless the transducer has an automatic self cleaning mechanism. Another way around this is to mimic some of the presented technologies above and utilize protective systems, which may be active or passive, to keep the transducer clean.

The only device from the overview that seems to handle both high temperatures and dirt deposits is the gap discharge emitter. As suggested by Tretiakov [30] when a gap discharge emitter is used combined with piezo-based transducers, only the capacity to deliver intense acoustic pulses is utilized. When the temperature starts to elevate and dirt deposits build up, that design will probably lack in performance. If a device could be constructed that utilizes only a gap discharge, it could be designed with only high quality metals and ceramics that could endure extremely high temperatures. Because the spark creates sound waves directly in the medium that carries the acoustic pulse to the receiver, it does not suffer from contamination in the same way as other devices. As long as the spark strikes properly, it produces sound waves. The possibilities of the gap discharge emitter make it the most interesting candidate for further investigation in this work. It will be described further in the next section.
3.1 The discharge emitter and its principles

The basic idea behind using a gap discharge emitter is simple: a sufficiently high electric field is applied between two conductors that are preferably made of a durable metal, such as tungsten. Dielectric breakdown of the gas between the electrodes results in a discharge that equalizes the potential between the electrodes. If the conditions are right, the discharge occurs rapidly, and a spark is formed in the conductive path. The spark rapidly releases heat energy to the surrounding air, and this leads to the formation of acoustic waves. The formed acoustic pulse contains a wide band of frequencies, and some have high amplitudes [23]. This is useful in applications that utilize acoustic pulses to perform measurements. The fact that the whole emitter can be built with durable materials makes it extra interesting for applications with very rough and difficult environments. In this thesis, the use of this technique in ultrasonic gas flow measurements is considered.

3.1.1 What motivates this technique?

Considering the gap discharge emitter from the environmental parameters listed in Section 2.1, the following can be assumed:

High temperatures Because all exposed parts in a discharge emitter can be constructed from high quality metals and non-conductive ceramics, the emitter itself can be built to handle very high temperatures of more than 1000°C. The long-term goal of this work is to develop transducers that can tolerate up to 1200°C.

Acoustic energy The acoustic pulses generated from a spark are generally very sharp and have high amplitudes. It is also possible to increase the power relatively easily by increasing the gap size and discharge energy.

Contamination It has been shown experimentally in paper B that a prototype device of the gap discharge emitter was able to maintain its performance when heavily
contaminated. The acoustic energy is created in the rapid heat energy emission from the spark directly in the gas. Thus, it is not dependent upon a surface to gas transition in order to put acoustic energy in the gas medium. The device is, therefore, far less vulnerable to surface contamination than traditional piezo-electric transducers.

**Pulse quality and impact on time of arrival estimation** The pulses emitted from a gap discharge emitter are proven to be detectable in experiments performed at industrial test sites in paper B. But as for the device itself, it is obvious that it cannot receive signals on its own. Therefore, it is dependent upon another type of technology to receive signals. However, it is capable of creating very intense acoustic pulses immediately in the medium that transfers the pulse to the receiver. One strategy is to develop a dedicated receiver from relatively conventional technology. If a transducer is constructed to work only as a receiver, it is easier to optimize and protect from harsh environments. Sound energy will probably be lost if there are protection barriers used around any transducer, both when emitting and receiving. Used only as receiver, the energy loss will be reduced, and combined with a loud emitter, such as the gap discharge device, the acoustic energy is more likely to be at detectable levels.

Given the arguments above, it is interesting to weigh the pros and cons identified for the gap discharge emitter from a gas flow meter perspective. Table 3.1 presents an overview of these properties.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Intense acoustic source</td>
<td>Emitter only</td>
</tr>
<tr>
<td>Robust and durable construction</td>
<td>Time jitter</td>
</tr>
<tr>
<td>Omni directional</td>
<td>Potential of self cleaning</td>
</tr>
</tbody>
</table>

*Table 3.1: The pros and cons of gap discharge emitter from a gas flow meter perspective.*

In Table 3.1, some new properties are introduced. Omni-directivity is a significant pro. This occurs in the radial plane of the spark and is derived from the symmetry of the spark. In the longitudinal plane, the emitted sound effect varies at different angles, however. A more theoretical description of the spark discharge as a sound generator has been described previously [32]. Another property is the potential for self-cleaning. The spark generates a rapid increase in temperature, both in the air between the electrodes and also on the spots on the electrodes where the spark originates. Any dirt stuck on the electrodes near the hot spots might be burned off by the spark. This has not yet been thoroughly investigated, though indications of these phenomena were observed in the environmental tests performed in paper B.
3.1. The discharge emitter and its principles

![Image of discharge emitter](image)

Figure 3.1: Long time exposure of several spark discharges. This picture illustrates the spatial fluctuations of the sparks. Millimeter scale is shown as reference.

![Graph of time vs. amplitude](image)

Figure 3.2: The resulting time jitter on received pulses from several spark discharges

A new parameter listed on the conside is time jitter. Time jitter is undesirable in flow measurements because it directly impacts measurement accuracy. Sound pulses emitted from a spark that strikes repeatedly between two electrodes vary slightly each time a spark is generated, see Figure 3.1. The spatial fluctuations of the spark impact the received pulses, as seen in Figure 3.2. The jitter in the received pulses is, however, not entirely due to spatial fluctuations. The initial power of the spark also affects the time stability of the received acoustic waves. The rapid spark discharge process leads to the formation of shock waves [26, 24, 33, 34]. This means that the acoustic energy initially travels faster than the speed of sound. The non-linear shock wave, however, ceases after a certain distance from the source, and the linear part of the acoustic energy dominates and
continues expanding at the current speed of sound in the medium. The initial distance at which the acoustic energy travels in the non-linear region varies depending on the energy in the discharge. This means that the time that the pulse uses to travel from the discharge emitter to the receiver partly depends on the intensity of the spark discharge because an intense spark generates a louder shock wave that travels faster than the speed of sound for a longer distance. An indication of this phenomenon can be seen in Figure 3.2, where the pulses with smaller amplitudes generally seem to have longer transition times. This is further discussed in Section 3.2.1. Both the above mentioned phenomena contribute to the overall time jitter; however, in larger geometries this inaccuracy will be shown to be tolerable.

3.1.2 Gap discharge emitter design

A gap discharge device in its simplest form only needs two electrical conductive electrodes connected to a voltage device that supplies sufficient voltage for a spark to occur. In order to make it useful, additional components are required. In this work, three different kinds of excitation electronics were used with different properties. Two different models of gap discharge emitters were also constructed: one was made entirely for lab usage with more flexibility but less mobility; the second was made for field tests at industrial test sites and was not very flexible but easier to handle and more robust.

3.1.2.1 Electronics design

As mentioned above, there were three different kinds of excitation electronics used to induce spark discharges. More strictly, it can be said that two main principles were used, and one had two different versions.

The first excitation circuit used in this work utilizes a high voltage power supply that is capable of producing voltages up to 30 kV. This power supply charges a capacitor that is connected in parallel with the discharge gap. In Figure 3.3, the capacitor is labeled $C$. When the capacitor charge reaches a sufficient voltage, the discharge occurs spontaneously. The repetition rate of the discharge can then be controlled by limiting the current that charges the capacitor, either by using any current controls in the high voltage supply or by using a high voltage resistor, marked as $R_c$ in the figure, in series with the high voltage supply and the capacitor. In the figure, a high voltage relay, $S_w$, can also be found as well as a dump resistance, $R_s$. These are used in order to safely remove any leftover charge in the capacitor when storing the equipment. The major advantage of this setup is the fact that the strength of the discharges is very consistent between the individual sparks. This circuit was only used in the lab for investigations of the behavior of the spark discharge generated ultrasonic waves.

The second excitation circuit is based on the principle of voltage transformation. A simplified circuit diagram is found in Figure 3.6. This principle utilizes an ignition coil transformer, $T_x$, that transforms low voltage transients into high voltage transients. The capacitance, $C$, is charged with rectified 220 VAC mains power, which results in a peak voltage of $\sim 320$ V, which is then discharged over the primary side of the transformer.
3.1. The discharge emitter and its principles

The voltage on the secondary side then reaches up to several kilovolts until the spark discharge occurs. With this circuit, it is possible to control the generation of the spark. This is accomplished by using a thyristor, which is labeled $Th$ in the figure, which keeps the discharge circuit open until given a trigger signal. When the trigger signal is given, it will close the circuit, and it remains closed until the voltage across it and/or the current running through it is below a certain holding level. This allows the capacitor to almost fully discharge through the primary side of the transformer, $Tx$, which transforms the voltage to the necessary levels for discharge to occur. A deeper explanation of thyristors can be found in standard electronics textbooks e.g. [35]. The drawback when using a thyristor is the fact that it keeps the circuit closed until the voltage across it and/or the current running through it drops below certain levels. This makes it difficult to use when several sparks must be set off at very short intervals. In order to enhance the repetition rate of the excitation circuit, another version was constructed in which the thyristor was replaced with an insulated-gate bipolar transistor (IGBT), which allows for fast on and off switching at a given command. This excitation circuit, with its two variants, was mostly used in environmental tests of the gap discharge emitting technique. It was constructed to be easier to handle in field and also to give the user the ability to control the discharge in order to adapt the concept to flow measurement systems. A picture of the latest version of this circuit, together with the ignition coil transformer, is found in Figure 3.4.

The most obvious difference between the two main excitation circuits is the ability to control the occurrence of the spark. Controlling the spark ignition is convenient when using the gap discharge emitter in a flow measurement system because it simplifies the time measurement operation. Another advantage with the transformed voltage circuit is the fact that it can be made almost entirely without using dedicated high voltage components. Only the cabling between the secondary side of the transformer and the discharge gap must be high-voltage specified. One trade-off with the transformed discharge circuit, however, is that the consistency between consecutively fired sparks is lower than that of

![Figure 3.3: Schematics of capacitance high voltage discharge circuit](image-url)
the first circuit with the high voltage supply. The acoustic amplitude received from these sparks has larger variation than that from the sparks generated with the high voltage supply circuit. A comparison can be found in Figure 3.5. Further description of the acoustic performance is presented in Section 3.2.1.

A circuit using a high voltage power supply that charges a high voltage capacitor can also be adapted to produce sparks at a given trigger command. This requires a fast and accurate high voltage switching device that also has the capacity to handle the relatively high peak currents that are generated when the capacitor discharges over the spark gap. This involves delicate electronics that will increase the cost and complexity.

3.1.2.2 Mechanical design

In this work, two different types of discharge gap emitters were manufactured: the first was made entirely for lab purposes, and the second was basically a prototype for field tests at industrial environments.

Figure 3.5: Comparison of pulses generated with a) High voltage discharge and b) transformed voltage discharge.
3.1. The discharge emitter and its principles

![Figure 3.6: Schematics of transformed capacitance discharge circuit](image)

### Figure 3.6: Schematics of transformed capacitance discharge circuit

The lab setup, Figure 3.7(a), was made to be adjustable in order to investigate different discharge gap lengths and angles. It consists of a rotation stage at the base, which is seen at the bottom of the figure. A metal plate is on the rotation stage; the plate holds two linear translation stages equipped with micrometers to precisely set the discharge gap. Each translation stage holds two blocks made of the polymer polyoxymethylene, which is commonly referred to as POM, that insulates the electrode holders. From the the polymer blocks and pointing upward are the electrodes that are made of tungsten. These electrodes are normally used for tungsten inert gas (TIG) welding and are very durable under these circumstances.

![Figure 3.7: a) The gap discharge made for lab tests and b) the gap discharge prototype used in field tests.](image)
The second discharge gap emitter, Figure 3.7(b), was made for in situ environmental tests at industrial process plants. This emitter had to be adaptable for the conditions given at the chosen test site and easy to transport and install. They were built on a modified 80-mm galvanized plug, which is seen at the bottom of Figure 3.7(b). A block of Polytetrafluoroethylene, PTFE, was fitted through a square hole in the plug to serve as an insulator for the electrodes. PTFE replaced the POM that was used in the lab setup because PTFE has higher temperature endurance and better corrosion resistance. These properties were believed to better suit the field test conditions. Four holes in the PTFE block served as guides for the steel rods that transferred the voltage potential to the electrodes. The electrodes were fastened in steel holders. Electrode materials for these emitters were of the same type as the lab setup, namely TIG welding electrodes. As seen in Figure 3.7(b), each emitter holds two pairs of electrodes and, thus, has two discharge gaps. This design was generated in order to compare the effect of the spark on the electrodes when exposed to contaminating environments. This is further described in Section 3.2.2.

3.2 Discharge emitter performance

Different experiments were performed to investigate the ability of gap discharge emitters to function as a crucial part of gas flow meter systems. The tests were divided into two categories: a test of the emitter as the sound source from a flow meter perspective, and a test of the ability of the emitter to handle rough environments.

The acoustic test is mainly performed to focus on the time jitter in the pulses from the emitter. This is important in order to establish an estimate of the accuracy of a gas flow meter based on this technology. Tests were also performed in industrial environments to investigate the acoustic behavior in real situations. The detectability of sound was also performed by integrating the gap discharge emitter with commercial flow meter electronics and piezo-based receivers.

3.2.1 Acoustic performance

The acoustic properties from the gap discharge emitter were investigated from different perspectives to evaluate its capabilities as a part of an ultrasonic flow meter system. The three main questions include the following:

1. **Pulse shape and amplitude** Is the emitted sound of such quality that it is possible to detect?

2. **Jitter** What is the extent of the jitter effect introduced by the gap discharge emitter caused by the spatial fluctuations and shockwave phenomena?

3. **Sound beam shape** The gap discharge emitter has round beaming capabilities. Are these beneficial when designing ultrasonic flow meter systems?
The acoustic signal emitted from a spark discharge contains a broad spectrum of frequencies [23]. In this work, the receiving device was a piezo-based 200 kHz transducer (Figure 2.1). This receiver acts as a pass band filter with a sensitivity window around 200 kHz. Examples of received signals with this receiver are found in Figure 3.8. In Figure 3.8(a) a typical single pulse is represented. In Figure 3.8(b) a set of 100 consecutively recorded signals is represented. In order to estimate the behavior from these pulses, they were synchronized in time. The result is found in Figure 3.8(c). The synchronization was performed according to the LSE method described elsewhere [36]. Data regarding jitter was extracted during the synchronization of the pulses. In Figure 3.8(d), an average of the synchronized pulses is presented. The amplitudes and sound pressures of the signal were not thoroughly investigated in this work. More focus was placed on investigating whether or not these parameters are sufficient in flow meter applications. The signals sent from a gap discharge emitter can be detected in industrial environments with bad conditions, as shown in paper B. Obviously, the sound strength and pulse shape are acceptable. In the performed tests, the receiving unit used a sample-and-hold zero detection algorithm to detect incoming signals.
As mentioned in Section 3.1.1, there are two main causes for the time jitter: spatial spark fluctuations and varying initial spark energy. Examples of spatial fluctuations are shown in Figures 3.1 and 3.2. The time jitter resulting from the spatial fluctuations alone generally have a standard deviation in the range 0.8\( \text{ns} \). Experiments were also performed in paper C to investigate the impact of energy variations in the spark. In Figure 3.9, the results from three measurements with different capacitances are shown. It is obvious that energy does seem to have a large impact on the transit times of the pulses. This motivates investigating how the energy strength impacts a real situation. In the experiment, the energy variations are quite large compared to the variations expected from the excitation circuit as the voltage transformation circuit described in section 3.1.2.1. Investigating the jitter from this circuit, which has contributions from both spatial fluctuations and varying spark energy, shows that the standard deviation of the jitter rises to around 1.5\( \text{ns} \). Clearly the varying initial energy in the spark impacts the jitter, but not as much as in the experiment presented in Figure 3.9. The variations in that experiment are larger than what seems to be reasonable from a circuit that is likely to be used with the gap discharge emitter, such as the transformed voltage circuit. These effects are more thoroughly described in paper C.

Another interesting feature of the gap discharge emitter is its ability to send acoustic energy in all directions. Because the spark behavior is symmetric in the radial plane, the
sound waves emitted will be omni-directional. A more theoretical description is provided elsewhere [32]. The beam profile in the longitudinal plane does not have the same level of symmetry and, therefore, does not have the same omni-directional properties. The beam profile in the longitudinal plane was investigated in paper B and C. A schematic view of the experimental setup used for these measurements is found in Figure 3.10. Examples of the measurements in the longitudinal plane are found in Figure 3.13. The amplitude is presented in dB, with 0dB defined as the amplitude at 0º. This figure is from the environmental tests to be described in Section 3.2.2. Studying the before curve shows that, at most, the signal loses almost 10 dB when listening at the sides at ±90º. Even though this is the non-symmetric plane, it still has far better omni-directivity than traditional ultrasonic transducers based on piezoelectric materials.

Another aspect of the acoustic performance is how it performs in a real environment. Tests in environments containing high levels of moisture and dust in the gas flow were performed to evaluate how the gap discharge emitter functions as an acoustic emitter. Figure 3.11 contains examples of how the signals behave under different conditions. Figure 3.11(a) is an example of a signal and its frequency content received in the lab, where the receiver is 2.9 meters from the emitter. Although the transducer is most sensitive around 200kHz the frequency content shows that a significant amount of energy lies in lower-frequency areas. Figure 3.11(b) shows a signal that has traveled through a \( \varnothing 1.9 \) meter exhaust gas chimney. This signal benefits from the shorter distance compared to the one in (a) from the lab and seems essentially unaffected by the environment in the chimney. In Figure 3.11(c), however, the diameter of the chimney is the same as in the lab, 2.9 meters, but the signal has lost a large portion of the frequencies and the pulse itself is altered to what was seen in the lab. The main reason for this behavior is that the conditions at the test site did not allow for proper alignment of the receiver to the emitter. Although this leads to a significant loss of acoustic energy in the receiver it still manages to deliver a detectable signal. This experiment is further described in paper B.
3.2.2 Environmental tests

In this section the environmental tests of the gap discharge transducer performed in this work are briefly described. The purpose of these tests was to investigate how the gap discharge emitter was affected by longer exposures to a harsh environment. Gas exhaust chimneys at an iron ore refinery served as test environments. Prototypes, as shown in Figure 3.7(b), were manufactured and connected to a transformed voltage excitation circuit. As seen in the figure, there are two available gaps on the prototype. During the test, only one of them generated sparks, periodically, and the other one was kept passive. This was done in order to investigate the potential for self-cleaning. The idea is that the intense heat generated during a spark discharge burns any deposits present on the electrodes. Figure 3.12 is a picture of one of the prototypes after the environmental test; it is quite heavily contaminated by dirt but still functional. Two prototypes with a total of four discharge gaps, two active and two passive, were used in this test. The acoustic properties of all four discharge gaps were measured before and after the test in order to identify any significant changes. An example of the results is found in Figure 3.13. The amplitude and jitter standard deviation before and after the test are presented. This figure is representative of the overall results of the test; the amplitude of the emitter is not significantly changed, and there are no drastic changes in the jitter. The prototypes were exposed to the test environment for approximately 1.5 months. The complete results from these tests are found in paper B. The detectability of the signals is investigated in Section 3.2.3.

Figure 3.11: The pulse characteristics in different environments: a) lab 2.9 m. b) exhaust gas chimney 1.9 m. c) exhaust gas chimney 2.9 m.
3.2. Discharge emitter performance

3.2.3 Gap discharge used in single loop transit time system

In order to test the quality of the emitted pulses from a gap discharge emitter, the emitter was integrated with commercially available flow meter electronics as seen in Figure 3.14. Thus, a closed measurement loop could be established using the gap discharge emitter as an acoustic source and a standard 200 kHz piezo electric transducer, seen in Figure 2.1, as a receiver. The emitted sound is received by the piezo-transducer and amplified. The amplified signal is then sent to an Application-specific integrated circuit (ASIC) that is custom-designed for ultrasonic flow metering. The ASIC normally works with two piezo electric transducers, but with some slight modifications of the surrounding circuit, it is used as seen in this setup (Fig. 3.14). The ASIC uses a zero crossing detection algorithm.
This means that the incoming signal must have an amplitude that is significantly higher than the measurement noise. This setup was tested both in the lab and in an industrial environment. It maintained stable operation in both the lab and the industrial site. Some disturbances occurred at one of the industrial test sites. These disturbances were due to the fact that the alignment of the piezo-transducer was not acceptable. A piezoelectric transducer is generally directional and will lose significant amounts of incoming acoustic energy if it is not aimed directly at the source. In this case, it led to some problems detecting all of the pulses, but it still managed to detect at least 90-95% of the emitted pulses. It is worth mentioning that this test was performed under non-optimal conditions to obtain a first estimation of performance in a realistic operation environment. There are many improvements that can be made. First, a more thorough installation in which more care is taken on the alignment of the piezoelectric transducer will dramatically improve performance. Additionally, by adapting the electronics detecting the incoming pulse and perhaps using a transducer that works in a different frequency span, further improvements may be achieved. Further details about this test are found in paper B.
Flow measurement with ultrasonic techniques

4.1 Method approach – Transit time

Flow meter systems can be very complex and there are many considerations in each situation. The aim of this chapter is not to give a thorough review but to provide a basic understanding of the benefits of gap discharge emitters.

In general, there are two types of ultrasonic flow meter methods used in closed pipe flow measurements: the first is called transmission and the second is called scattering. Scattering will not be explained further in this work; further details can be found elsewhere [37].

The transmission method normally includes sending and receiving short duration ultrasonic pulses. One variant commonly used is the transit time flow meter. A functional sketch of a transit time flow meter is found in Figure 4.1. In this figure a system consisting of two transducers diagonally oriented according to the flow direction is presented. Both transducers send and receive pulses to and from the other one. The pulses are sent along the diagonal path with length $L$ at an angle of $\alpha$ degrees to the flow that moves with average velocity $V$. The pulses that are sent downstream have transit times according to equation (4.1) and upstream according to equation (4.2). $C$ corresponds to the speed of sound in the medium.

$$t_1 = \frac{L}{c + V \cos \alpha} \quad (4.1)$$

$$t_2 = \frac{L}{c - V \cos \alpha} \quad (4.2)$$

From equations (4.1) and (4.2), the velocity $V$ can be resolved, which gives equation (4.3). Velocity $V$ is then the average fluid flow speed along the sound path $L$. 

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Flow measurement with ultrasonic techniques

V = \frac{L}{2 \cos \alpha} \left( \frac{1}{t_1} - \frac{1}{t_2} \right) \quad (4.3)

Please note that these equations are based on a number of assumptions. The speed of sound, c, is assumed to be constant along the upstream and downstream transit time estimations. If this assumption is not made, it is not possible to eliminate c from the final expression. Another assumption is that the acoustic travel path is straight. In real situations, the received acoustic pulse will have followed a slightly curved path due to the flow velocity of the medium. This assumption is valid if \( V < < c \). Typically, this occurs if the flow velocity is lower than Mach 0.1 [37]. Regardless of the assumptions made, the derived expressions make it easier to understand the impact of different parameters when designing a transit time ultrasonic flow meter system. Because the flow is calculated using the difference of the transit times, \( \Delta t \), the timing of the system is most crucial. Other components that affect the accuracy include the flow velocity, \( V \), and the length of the acoustic path, \( L \). The accuracy suffers with lower velocities because \( \Delta t \) is smaller, which increases the impact of any error sources and/or noise in the measurements. The velocity is of course dependent upon the application and has to be considered for each given situation. An easier approach to increase \( \Delta t \) is to design the system with a smaller angle \( \alpha \) to increase the acoustic travel path \( L \). This is possible to some extent, but if \( L \) is increased too much, the signal emitted from the transducers might not be loud enough to be detected by the receiving side.

Another limitation lies in the determination of \( V \). The flow in the pipe might have a varying flow profile along the centerline. Examples of this in 2D are found in Figure 4.2. In this figure, laminar flow, turbulent flow and disturbed flow profiles are shown where the flow velocity varies across the cross section of the pipe. This means that, when calculating the velocity according to Equation (4.3), one determines the average velocity along the centerline of the pipe. Taking into account the fact that only a small...
4.1. Method approach – Transit time

Fraction of the fluid actually flows in the center of the circular pipe compared to the sides, one realizes that the calculated velocity might not be correct. In Figure 4.4 four different areas in a circle are shown together with their respective fraction of the total area. Combining the facts that are given in Figure 4.2 makes it obvious that a pulse traveling through the diameter path will have its average velocity affected equally by the smaller areas and the larger areas in the pipe. This means that the average velocity calculated is not weighted to the flow distribution and is not a good representation for the average flow in the pipe. For example, the smallest area in the middle corresponds to 6% of the area but as much as 25% of the total path length along, which the average velocity is calculated. To overcome this problem, a system consisting of several acoustic paths can be constructed: a multipath system. The paths can be chosen in many different ways depending on different situations. The multipath solution, however, increases the complexity of the system because each path requires two additional transducers. Several paths rapidly increase the cost of the system in all aspects: purchase, installation and maintenance.

The size of a pipe containing a fluid, liquid or gas, flow affects the flow profile of the fluid. The primary use of gap discharge emitters is in large industrial applications. In order to estimate the flow profile in a pipe, the Reynolds number, $R_e$, can be calculated according to equation (4.4):

$$ R_e = \frac{\rho V D}{\mu} $$

where $\rho = 1.2 \text{kg/m}^3$ and $\mu = 18.4 \cdot 10^{-6} \text{kg/m} \cdot \text{s}$ for air at atmospheric pressure and room temperature. Turbulent flow generally occurs at Reynolds numbers larger than 4000 [37]. For a pipe with a diameter of 0.5 meters, this occurs at about 0.122 m/s with air as the flowing medium. This velocity limit gets even lower as the pipe diameter increases. The most ideal environments for a gap discharge emitter are large-geometry applications in industry. This means that, in most cases, the flow is turbulent, as in Figure 4.2(b), unless the mean flow velocity is extremely low. It is not necessary for the flow velocity to be symmetric, and it might be asymmetric because of different kind of installation effects, [37]. A sample asymmetric flow profile is shown in Figure 4.2(c). The need for multipath capabilities is, therefore obvious. Different solutions and benefits of multipath

Figure 4.2: Example of velocity profiles in a closed pipe with a flowing medium a) laminar flow b) turbulent flow c) distorted non-symmetric
flow meters have been discussed [37, 38].

4.1.1 Gap discharge emitter in flow meter systems

The gap discharge emitter gives new possibilities when designing multipath flow meters. The emitter ability to act as a spherical sound source means that one emitter can serve several receivers both upstream and downstream. As a result, a single shot from the gap discharge emitter can be received simultaneously both upstream and downstream, which allows the mean velocity along several acoustic paths to be calculated at the same time. If a higher level of intrusion is allowed, it is also possible to install a gap discharge emitter in the center of the pipe with several receivers placed on the wall upstream and downstream from the emitter. An example configuration can be seen in Figure 4.3(b), where five paths are used. In Figure 4.3(a), a classical example with directional transducers is shown.

Because the gap discharge emitter is also a relatively loud acoustic source, it is possible to design flow meters with longer acoustic paths. This is desirable if the geometry at the test site is large and/or if the flow velocities are low. Low flow velocities decrease the accuracy of a transit time flow meter, and in order to compensate for this, the acoustic path can be made longer, as discussed in Section 4.1.

To get a deeper understanding of the influence of the involved parameters, uncertainty analysis can be performed to calculate the uncertainty magnification factors (UMFs). A general uncertainty analysis performed according to a previously defined method [39] with Equation (4.3) as the data reduction equation results in the expression found in

\[
\text{(4.3)}
\]

Figure 4.3: Example of multipath configuration with a) traditional transducers and b) gap discharge emitter with traditional receivers.
4.1. Method approach – Transit time

Equation (4.5):

\[
\left(\frac{U}{V}\right)^2 = \left(\frac{U_L}{L}\right)^2 + \left(\frac{\alpha \tan \alpha}{UMF_{\alpha}}\right)^2 \left(\frac{U_{\alpha}}{\alpha}\right)^2 + \left(\frac{t_2}{l_1 - t_2}\right)^2 \left(\frac{U_{t_1}}{t_1}\right)^2 + \left(\frac{t_1}{l_2 - t_1}\right)^2 \left(\frac{U_{t_2}}{t_2}\right)^2
\]  

(4.5)

where the uncertainty U of the average velocity V can be estimated. The estimated uncertainty for each variable is denoted by a subscript, for example \(U_L\) is the uncertainty of L. \(U/L \times 100\) can be used to get the estimated uncertainty percentage of the measured average flow velocity. From Equation (4.5) it can be seen that all parameters except L have UMFs. This means that their contribution to the general uncertainty differs depending on different settings. For example, considering \(\alpha\), the influence grows slowly initially and increases dramatically when \(\alpha\) approaches 90°. In other words, when \(\alpha\) grows to larger values, it is more crucial to have an accurate value than for smaller values of \(\alpha\). The UMFs for \(t_1\) and \(t_2\) are similar to each other. Thus, for small values of \(\Delta t\), \(|t_1 - t_2|\), the impact of the timing errors, \(U_{t_1}\) and \(U_{t_2}\), is larger.

The jitter introduced by a gap discharge emitter only impacts on the timing errors, \(U_{t_1}\) and \(U_{t_2}\). To estimate the extent of the impact, we assume that \(U_L\) and \(U_{\alpha}\) are zero. Thus, only the timing error uncertainties remain. In paper C, it is shown that, when a gap discharge emitter is used with a voltage transformation excitation circuit (Section 3.1.2.1), a standard deviation \(\sigma = 1.61\mu s\) is reported. This is the largest \(\sigma\) reported and is representative of a worst case scenario. It is probably larger than what is expected from a system that has been carefully designed and adapted for gap discharge emitters in flow meters. Additionally, by averaging several pulses to estimate travel times, the uncertainty is reduced. However, in order to estimate the impact of jitter distributions in these magnitudes, we consider some cases in which \(\sigma = 1.5\mu s\). Assuming a normally distributed jitter, a 95% interval would then be \(2\sigma = 3\mu s\). Using this value as \(U_{t_1}\) and \(U_{t_2}\) in a simulated flow situation and calculating the error for different parameter settings gives an overview of the impact of jitter on the error. The results from these simulations can be found in Figure 4.5. This figure contains three graphs; each graph represents a

Figure 4.4: Area fractions of a pipe.
flow meter system as seen in Figure 4.1 but with different values of $\alpha$: 60°, 45° and 30°. Each graph has four curves that represent the four different pipe diameters. The X-axis represents the flow velocity, and the Y-axis represents the estimated uncertainty when using $2\sigma=3\mu s$. The worst conditions are found for $\alpha=60^\circ$, when the acoustic travel path $L$ is shortest. In a $\varnothing0.5m$ pipe 2% accuracy is never achieved for flow velocities lower than 30 m/s. For a $\varnothing1.5m$ pipe, a flow of at least 13 m/s is required to achieve less than 2% uncertainty. For smaller values of $\alpha$ the required conditions are more reasonable. When $\alpha=30^\circ$, a $\varnothing1.5$ m pipe only needs a flow velocity of about 5 m/s to achieve 2% accuracy. For the same $\alpha$ in a $\varnothing0.5$ m pipe, 5% accuracy is reached just under 6 m/s. Even with $\sigma$ as large as in this example, it is shown that it is possible to reach fair accuracy within reasonable limits based on the jitter that comes from the gap discharge emitter.

As a comparison to the worst case scenario another example is presented in Figure 4.6. Here the standard deviation is defined as $\sigma=0.7\mu s$. This value is on the same order of magnitude as the lowest $\sigma$ reported in the measurements presented in paper C.

Due to the nature of the gap discharge emitter, it can be concluded that it is best suited for large geometries. Because it introduces jitter in the measurements, it will suffer if used for distances that are too small. This will, however, be compensated for when used in large geometries. There is also the possibility of designing the system to achieve longer acoustic paths to suppress the impact of jitter. The gap discharge emitter is also advantageous for hot and dirty gas flows. The results from paper B demonstrate that the acoustic performance does not show any significant deterioration after long-term exposure to a harsh environment. Additionally, if allowed to operate under optimized conditions, it shows good potential for real applications.

A gap discharge emitter can be built entirely with high quality metals and ceramics, and therefore, a high-temperature design is realistic. The limitations probably lie on the receiving side. In order to get matching performance on the receiving side, either new technology needs to be developed or existing technology needs to be modified. Modifying existing technology is tricky and probably includes compromises. One advantage is that modifications can be made while focusing solely on a dedicated receiver.
4.1. Method approach – Transit time

Figure 4.5: Uncertainty analysis for transit time flow meter system with a worst case scenario timing error of $2\sigma = 3\mu s$ in pipes with different diameters and with an acoustic travel path angle $\alpha$ of a) $60^\circ$, b) $45^\circ$ and c) $30^\circ$ to the flow.
Figure 4.6: Uncertainty analysis for transit time flow meter system with a timing error of $2\sigma = 1.4\mu$s in pipes with different diameters and with an acoustic traveelpath angle $\alpha$ of a) 60°, b) 45° and c) 30° to the flow.
5.1 Paper A - Mechanical thermal expansion correction design for an ultrasonic flow meter

Authors: Emil Martinson and Jerker Delsing

Published: presented at 14:th FLOMEKO, Johannesburg, South Africa, September 2007

Summary: In this paper the concept of automatic corrections in a transit time/sing around flow meter system is investigated. When a transit time/sing around flow meter system is subjected to changes in the ambient or fluid temperature the materials in the meter will expand. This changes the geometry and causes a bias error in the measurements. By inserting compensation bodies behind the transducers, the effect of thermal expansion in the meter materials is reduced. Both mechanical and system simulations are performed to verify the results. The system simulations are performed on a fully modeled ultrasonic transducer system built in the industrial standard, PSpice. The results show that the influence of thermal expansions can theoretically be reduced to a negligible level.

5.2 Paper B - Environmental tests of spark discharge emitter for use in ultrasonic gas flow measurements

Authors: Emil Martinson and Jerker Delsing

Published: presented at 7:th ISFFM, Anchorage, Alaska, USA, August 2009

Summary: In this paper environmental tests were performed on gap discharge emitter prototypes. The tests were performed in industrial environments that included
heavy surface contamination, moisture, dust and moderate temperatures. The tests were performed in two categories: testing the effects of long term-exposure in a harsh environment and testing the acoustic performance in the same environment. The long-term test showed that the performance of the gap discharge emitter did not show any significant deterioration. The acoustic tests showed that sound signals that are feasible for flow measurement under poor conditions were obtained.

5.3 Paper C - Study of electric gap discharge as an ultrasound generator in flow measurement situations

Authors: Emil Martinson and Jerker Delsing

Published: Journal paper, to be submitted

Summary: In this paper, the ability of gap discharge emitters to work as a sound source is investigated. The gap discharge emitter produces unwanted jitter in its acoustic pulses. This jitter is partly due to the spatial fluctuations of the spark and partly due to the variations in amplitude of the emitted sound. The contributions of these phenomena are analyzed and quantified. The acoustic beam profile from the gap discharge emitter is also presented. The impact of the measured jitter distributions in various flow meter situations is discussed.


6.1 Conclusions

In this thesis, the possibility of using ultrasonic flow metering in extreme environments is investigated. The early work focused on the gap discharge emitter. As a result, using an electric spark discharge to generate ultrasound appeared to be a feasible alternative to be used in environments with extreme conditions. The gap discharge emitter was evaluated for its ability to withstand harsh environments and its ability to act as an ultrasonic emitter for gas flow measurements. It was tested under harsh conditions that included heavy contamination, moisture, dust and moderate temperatures. The results from these tests demonstrated that the emitter was basically unaffected, even when covered with thick layers of dirt. There were also no apparent obstacles to adapting the gap discharge emitter to high temperature environments. The gap discharge emitter was also proven to be durable in a rough industrial environment. It was not dependent upon any delicate mechanical or electrical constructions; moreover it was possible to use it together with commercial flow meter parts without any further modifications. Finally, it is just as easy to install and handle as existing systems in the same area.

The hypotheses stated in Chapter 1 was: Ultrasonic gas flow measurement techniques can be applied in industrial applications that include extreme environments that include temperatures up to 1200°C and the presence of contaminating dirt, dust, high moisture content, atmospheric pressures and large geometries. Two research questions was raised

1. What kind of transducer technology can operate in a flow metering system under the given extreme conditions?
   The results in this work clearly demonstrate that it seems possible to use the gap discharge emitter as an ultrasonic transmitter in a gas flow measurement system in extreme environments. This work did not address the possibility of developing a receiving device. That is part of future work.

2. What performance will a flow meter system with this technology have?
   If proper care is taken when designing a gas flow meter with gap discharge emit-
ters, they will not suffer from the introduced time jitter. They can endure rough environments for longer time periods without the performance suffering. Moreover, they emit intense pulses that can be used for ultrasonic flow measurement in large geometries. The results in this thesis support using the gap discharge emitter for industrial gas flow meter applications.

6.2 Future work

The biggest remaining portion in the future work for this project is the development of a receiver that can work under the same conditions as the gap discharge emitter. The complete ultrasonic gas flow meter system for extreme environments will not be a reality until a receiver exists as well. There are two ways to for future development: 1. Modify existing technology; 2. Develop new technology. Existing technology can be modified with a focus on building a dedicated receiver. Adapting the technology that exists today to extreme environments will most likely need to include a protection system to spare the transducer used. This will probably compromise the transducer sensitivity because any protection barrier reduces incoming signal amplitude. If current technology were to be adapted to both transmit and receive ultrasonic pulses it would lead to a reduction in signal amplitude in both ways. Utilizing an intense transmitter, such as a gap discharge emitter, it would be easier to use a protected dedicated receiver and still have enough signal strength to detect incoming signals.

Extended environmental tests are also part of future work. First, it is necessary to perform long-term tests in order to estimate the necessary service interval terms for a gap discharge emitter and to determine its expected lifespan. It is also necessary to design a high temperature prototype and evaluate it in extremely high temperatures up to 1200°C. This must be done in order to analyze how the emitted acoustic pulses change with elevated gas temperatures.
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Mechanical thermal expansion correction design for an ultrasonic flow meter

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Mechanical thermal expansion correction design for an ultrasonic flow meter

Emil Martinson and Jerker Delsing

Abstract

When an ultrasonic flow meter system using the transit time technique is subjected to an increasing ambient or fluid temperature, the material in the meter will expand due to thermal expansion. This will affect the measurements due to a mismatch between the calibrated lengths in the meter system and the true lengths that varies with temperature. This paper incorporates a simple idea to reduce this problem. By the insertion of a compensation body behind the transducers the thermal expansion of this body will work to compensate for the errors due to the expansion in the materials that the flow meter is made of. Simulations have been performed to verify the idea and they show on a high level of compensation for the mentioned errors. The influences from thermal expansions can theoretically be reduced to a negligible level.

1 Introduction

Ultrasonic measurements are commonly used today and one of the areas is in flow measurements [1]. When measuring fluid velocities the equipment might get exposed to apparent changes in temperature, ambient or in the fluid, and this fact raises a number of issues. Several parameters that affect the measurement results are temperature dependent, e.g. flow velocity, fluid density, fluid viscosity and thermal expansion in materials [2]. In this paper the effects of thermal expansion are considered and how to reduce the error they might give on performed measurements.

2 Theory

The calculations and simulations in this work have been made on an ultrasonic flow meter measurement system based on the transit-time technique used in a simple geometry, see fig 1.

In a transit-time measurement system the speed of the medium, a liquid in this example, is determined by measuring the time of flight difference between ultrasonic pulses that travels down- and up-stream in the fluid between the transducers. The differences in time of flight is due to the fact that the speed with which the ultrasonic pulses travels between the transducers depends on the speed of sound in the fluid, $c$, and the speed of the fluid itself $V_f$. This leads to a shorter transit-time when an ultrasonic
pulse is traveling downstream. The total time for a pulse traveling downstream, from
transducer 1 to transducer 2, can then be expressed according to eq. (1) with \( L_f \) being
the length the pulse travels in the fluid from transducer 1 to transducer 2. Equation (2)
represents the transit-time in the opposite direction, upstream.

\[
t_1 = \frac{L_f}{c + V_f} \tag{1}
\]

\[
t_1 = \frac{L_f}{c - V_f} \tag{2}
\]

From equations (1) and (2) an expression for the velocity of the fluid can be derived
that is independent of the speed of sound in the fluid:

\[
V_f = \frac{L_f}{2} \left( \frac{1}{t_1} - \frac{1}{t_2} \right) \tag{3}
\]

Equation (3) does not express the whole truth. In a real situation the average ve-
locity of the fluid in the passage might not be representative to the velocity that the
ultrasonic pulse experience. The velocity profile in the fluid passage is probably not
evenly distributed and might depend on several factors such as geometry, fluid velocity
and fluid properties. The nature and effects of these phenomena are further described
by Lynnworth [1]. In order to reduce complexity and increase focus on the main idea
however, these effects were not taken into account for in this paper.

By developing eq. (3) further it is also possible to calculate the volume flow in the
same passage by multiplying \( V_f \) with the area of the fluid passage, \( A_p \):

\[
\text{Vol}_f = \frac{A_p \cdot L_f}{2} \left( \frac{1}{t_1} - \frac{1}{t_2} \right) \tag{4}
\]

By studying eq. (3) and (4) it is found that the system depends on a predetermined
and constant length between the transducers, \( L_f \). This leads to a problem if drastic
temperature changes are introduced. The length \( L_f \) is a subject to change due to thermal
expansions if the temperature increases or the opposite if the temperature decreases. A
larger effect is introduced if the volume flow is measured since the fluid passage area
changes with the square of the diameter change. Assume the material in the fluid passage
has a thermal expansion coefficient, \( \alpha_p \), and the temperature change is equal to \( \Delta T \), then
the length that the ultrasonic pulse will have to travel in the fluid will change according
to:

\[
L_{FT} = L_f (1 + \alpha_p \cdot \Delta T) \tag{5}
\]

Where \( L_{FT} \) is the length with thermal changes taken into account and \( L_f \) turns into
a constant that have to be decided at a reference temperature, \( T_{ref} \), preferable the same
temperature that any calibration is performed at.

The concept presented in this paper is an idea to compensate for these changes in
a simple and reliable way. The principle is to insert compensation bodies behind the
transducers, as shown in fig. 1, and let them compensate for the thermal changes in length between the transducers. The idea to use this kind of compensation in this type of measurement setup is introduced by Delsing [3]. If for example the temperature increases and the length between the transducers increases according to eq. (5), the length of the compensation bodies is also increased and thus the transducers is kept at a constant distance from each other. If the material in the compensation bodies has a thermal expansion coefficient, $\alpha_c$, that is larger than the same coefficient for the fluid passage, $\alpha_p$, the length of the compensation bodies can be reduced.

Assume that the length from the backside of the first compensation body to the backside of the other at $T_{ref}$ is $L_b$ and the individual length for each compensation body is $L_c$ at $T_{ref}$. Expressions for their temperature dependence look similar to eq. (5):

$$L_{bt} = L_b (1 + \alpha_p \cdot \Delta T)$$

(6)

$$L_{ct} = L_c (1 + \alpha_c \cdot \Delta T)$$

(7)

The key to get the compensation to work as intended is to adapt the length $L_c$ at temperature $T_{ref}$ such that the length of the compensation bodies will change in order to achieve minimum influence from the length changes in the fluid passage. If the system is performing measurements to calculate the fluid velocity the parameter of influence is the length $L_{ft}$. $L_{ft}$ can be expressed in terms of eq. (6) and (7):

$$L_{ft} = L_b (1 + \alpha_p \cdot \Delta T) - 2 L_c (1 + \alpha_c \cdot \Delta T)$$

(8)

In order to decide the desired $L_c$, the derivative of $L_{ft}$ with respect to $\Delta T$ is set equal to zero and solved for $L_c$. In this way the length for $L_c$ that has a minimum influence on $L_{ft}$ is determined:

$$L_c = \frac{L_b \alpha_p}{2 \alpha_c}$$

(9)

Actually, when $L_c$ is adapted as in eq. (9) the theoretical compensation is 100% since the compensation bodies are able to keep the length between the transducers constant.

---

**Figure 1: Ultrasonic flow meter with compensations bodies**
When measuring volume flow the result is unlike velocity measurements not only affected by the length change between the transducers, in that case the cross-sectional area of the fluid passage must also be considered. If the fluid passage is assumed to be circular the cross-sectional area will depend on temperature changes according to:

\[ A_{pT} = \frac{\pi}{4} d^2 \left(1 + \alpha_p \Delta T\right)^2 \]  

(10)

Since the area will change with the square of any change in the diameter, it is not possible to achieve full compensation with the method presented in this paper. It is still possible to reduce the error significantly. To find out how to adapt the compensation bodies for this the temperature dependence for volume flow measurements must be studied. The volume flow is calculated according to eq. (4). By replacing \( A_p \) and \( L_f \), with \( A_{pT} \) and \( L_{fT} \) a temperature dependent version of that equation is achieved. \( A_{pT} \) and \( L_{fT} \) are the parts that involve the temperature dependence that is to be reduced. The product between them can be seen as the volume of the fluid passage that is between the transducer surfaces. This cylindrical volume is changing with varying temperature since both its length and area are affected. The compensation bodies adapt the length of this volume to maintain the volume as constant as possible with varying temperature and thus keep the volume flow measurements accurate. To find the proper length of each compensation body the derivative of this temperature dependent volume with respect to \( \Delta T \) is set equal to zero and solved for \( L_c \), resulting in:

\[ L_c = \frac{3}{2} \cdot \frac{\alpha_p L_b (1 + \alpha_p \Delta T)}{2 \alpha_p + 3 \alpha_p \alpha_c \Delta T + \alpha_c} \]  

(11)

Equation (11) thus shows the optimal length for each individual compensation body, \( L_c \), at \( T_{ref} \), to achieve maximum compensation when measuring volume flow with the above described method and geometry. Note that \( \Delta T \) is involved in this expression indicating that there is no optimal length for the compensation bodies that will give 100% compensation for all temperatures. In order to get an absolute length for the compensation bodies \( \Delta T \) in eq. (11) must be set to a value. This value will affect how the compensation behaves along the temperature range.

3 Simulations

3.1 Mechanical simulation

In order to get an estimation of how the described method works simulations have been performed using the equations derived in the previous section. First purely mechanical simulations were performed in MATLAB. The mechanical simulations shows in what order the errors due to thermal expansion are and how much the compensation bodies reduce them. In the model used in the simulations the fluid passage is made of Polyvinyl chloride (PVC) with a thermal expansion coefficient \( \alpha_p = 100 \cdot 10^{-6} \, ^\circ C^{-1} \) [4] and the compensation bodies are made of low density polyethylene (LDPE) and have the
corresponding $\alpha_c = 300 \cdot 10^{-6} \, (\degree C)^{-1}$ \cite{4}. Comparisons between a model without compensation bodies and a model with compensation bodies were calculated. It is assumed that a system performing measurements of this kind has been calibrated at a certain $T_{ref}$ and thus have a defined length $L_f$ and area $A_p$ that it uses when calculating pulse velocities. In the simulations the errors were defined as the deviation from these values on the corresponding temperature dependent variables $L_{fT}$ and $A_{pT}$.

\section{3.2 System simulation}

The other set of simulations made were performed on a fully modeled ultrasonic transducer system in order to test the concept on a more complex model, from excitation electronics to acoustic wave propagation to receiving transducer and back to an electric signal. The model is built in PSpice which is an environment to simulate electronic systems. By introducing a series of electrical-acoustical analogies the acoustical parts of the model can be simulated at the same time. The block schedule of the model can be seen in fig. 2. The model used is described more detailed by Deventer et al. in \cite{5}.

In these simulations the compensation bodies were applied and adapted to correct for thermal influences on the geometry. A static flow rate was defined and the fluid velocity were calculated for the different $\Delta T$ with respect to the change in fluid passage area $A_{pT}$. The velocity profile acquired in the simulated temperature range affected the ultrasonic pulse travel times $t_1$ and $t_2$. These travel times were then inserted in equations (3) and (4) to get the values for velocity and volume flow measured by the modeled system.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{pspice_model.png}
\caption{Block schedule of the ultrasonic flow meter model in PSpice}
\end{figure}
4 Results

Fig 3 shows the results from the simulations. In 1.3(a) the dotted line represents how the error would look like if velocity measurements are made with no compensation for thermal influences on the geometry. The solid line represents the measurements with thermal compensations applied. As expected the compensation in this case is 100% and the errors disappears when the model includes the compensation bodies. The ‘x’ marks the results from the full system simulation performed and agrees very well with the mechanical simulations.

![Graph showing results](image)

Figure 3: Results from simulations

Fig. 1.3(b) shows corresponding simulations for the system performing volume flow measurements. If no compensation is applied the errors in this case are larger than errors that can arise when only measuring the fluid velocity. The compensation however manages to almost completely reduce these errors. Comparing to the errors with no compensation the errors still present with the compensation applied is negligible.

For further investigations around volume flow compensation fig. 4 can be studied. As discussed in section 2 around eq. (11) there were different options when deciding the length \( L_c \) for the compensation bodies since \( \Delta T \) had to be assigned to a value. One of the curves in fig. 4 shows \( L_c \) decided according to eq. (11) with \( \Delta T \) set to 0 and the other curve when \( \Delta T \) is set to 23°C. Comparing the two curves shows that the compensation differs in the simulated temperature range. It can be stated that the different curves seems to compensate more or less accurate depending on what temperature variations are to be expected. Worth noticing in this case however are the extremely small deviations on these curves, only around 0.01% and less, so both of them can in most cases be seen as almost equal to each other when other sources of errors are more likely to be more dominating.

Over all the idea with transducers mounted on compensation bodies that are adapted
to correct errors caused by thermal influences on the geometry seem to work well. The performed simulations gives a hint that a high level of compensation can be expected with this idea when only the geometrical aspects are considered along with temperature changes. Of course there are other temperature dependent factors that might affect the errors in the measurements as well but in this paper the focus has been on the ones caused by thermal expansion in the materials.
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Environmental tests of spark discharge emitter for use in ultrasonic gas flow measurements

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Environmental tests of spark discharge emitter for use in ultrasonic gas flow measurements

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Abstract

In some situations, the ability to measure gas flows can be very limited due to difficult environmental conditions. Examples of such conditions identified in real situations include very high temperatures of up to 1200°C, low pressure gas, high humidity, dust, heavy surface contamination and large dimensions (1-5m pipe diameters).

In this paper, we investigate the performance of the only ultrasound emitter type we expect to be able to handle the mentioned conditions. The transmitter has been developed for harsh condition gas flow measurement using the approach of transit time or sing around technology for flow metering. Tests have been performed in a real environment in the iron ore process industry. The testing environment includes gas flows with condensing moisture, moderate temperatures and heavy surface contamination.

The device investigated for the emission of ultrasound uses the principle of electric gap discharge to obtain acoustic pressure waves. Since all exposed parts of the emitter can be made using high quality metal and ceramics if necessary, it can be designed for very high temperatures, with a goal of reaching around 1200°C.

The tests performed here are divided into two categories: the effects of long term exposure in a bad environment and the sonic performance in the same environment.

The first test revealed that both emitters were capable of surviving the contamination problem and could still work after almost 1.5 months in the environment. The signal amplitude difference before and after the test was less than 5%. In some cases the signal was stronger after the test than before.

The second test showed that sound signals feasible for flow measurement under high dust content and high humidity were obtained. This was shown under realistic operation conditions in an iron ore pelletizing plant. The sound path varied from 1.9 – 3m, and the temperatures were moderate, around 30-80°C.

From the results in these two tests it can be stated that the idea of using a gap discharge emitter in the above mentioned conditions is a promising way to generate ultrasonic pulses for flow measurements in difficult and unfriendly environments.

1 Introduction

Ultrasonic flow measurement is a convenient way to obtain accurate and reliable flow measurements [1]. It is also easy to integrate into existing process plants and is therefore suitable for installation at older sites that currently lack efficient flow measurements. In
some places, however, the lack of installed flow measurement systems is partially due to the harsh environments presented, which will put heavy demands on any installed equipment. Ultrasonic transducers may experience trouble if exposed to contaminating dust, high temperatures and high moisture [1]. In particular, the transducers ability to maintain sufficient amplitude on the emitted sound pulses will be tested, especially if used in gas flows with low pressure, large geometries and high contamination exposure.

Piezoelectric transducers are commonly used for ultrasonic applications; they are developed in a broad spectrum with one focus being on high temperature. There are reports of piezoelectric ceramic films tested at 800°C by Kobayashi et al. [2], although these were not tested in gas. There are other promising techniques under development that also deal with high temperature gas transducers. Schröder et al. [3] have successfully manufactured and tested a capacitive ultrasonic transducer (CUT) in temperatures up to 600°C, and there has also been work done to improve these [4]. There is also a method to protect the transducer itself from the hot medium by using, for example, a buffer rod between the transducer and the medium, [5]. Active cooling is another approach and can be found in different commercial products where, for example, air is used as the coolant. However, when the environment also contains other difficult conditions such as heavy dirt deposition, as seen in fig. 4, any transducer that uses a surface to medium acoustic connection to transfer acoustic energy will be limited. The need for special protection arrangements will increase in order to maintain performance.

In this paper, a transducer that specializes in the creation of ultrasonic pulses in the above mentioned environments is evaluated according to its ability to withstand difficult conditions. The work in this paper is one step towards the goal of a gas flow meter system that can withstand conditions such as extreme temperatures, <1200°C, low pressure, high humidity, dust, heavy surface contamination and large dimensions (1-5 m pipe diameters). The transducer uses the principle of electric gap discharges in air. A spark is generated during a rapid dielectric breakdown of the air between two electrodes. During the spark generation the air in the vicinity of the spark column will then heat up very rapidly. This will cause a sharp and broadband acoustic pulse with high amplitude. This pulse can then be used to measure transit times in a transit time or sing around ultrasonic gas flow meter. Since the exposed part of the transducer can be made of high quality metals and ceramics it can be built to withstand high temperatures. The creation of sound is also made directly in the gas so there is no dependence on a surface to medium transition of the acoustic energy and therefore the sensitivity to dirt deposits is smaller. As long as the spark is able to strike, sound waves will be created. This also has the potential of self cleaning since the spark acts to burn away any deposits on the electrodes.

The objective of this paper is to investigate this type of device’s durability against rough environments. Therefore, it was tested in an exhaust chimney at a mining company. The test environment includes contaminating dust, moisture and moderate temperatures.
2 Experiments

The tests performed on the gap discharge emitter in this paper were divided into two parts: the effects of long term exposure in a harsh environment and the acoustic performance in the same environment. The long term environmental test was conducted to evaluate how the emitter is affected by mainly heavy dirt deposits. The acoustic performance test investigated the emitter’s capability as a sound emitter in harsh environments.

2.1 Long time environmental test

In order to investigate how a gap discharge sonic emitter performs after a longer period in a demanding environment two prototypes were constructed, each as seen in fig. 1, and installed in a process plant at a mining company. The test environments were exhaust gas chimneys containing gas flows consisting of mostly air, dust and condensing moisture, see table 1. The prototypes were each mounted in two different chimneys with similar gas flows, referred to in this paper as chimney 1 and chimney 2. The gas flow in chimney 1 generally contains more dust, while chimney 2 has a higher moisture content. Each prototype also includes excitation electronics in order to periodically generate sparks with a frequency of ∼3Hz. In fig. 1 it can be seen that the prototype model consists of two pairs of electrode holders. This means that it has two available discharge gaps. During the environmental exposure, only one of the discharge gaps at each prototype was used to generate sparks. The other one was kept passive. This was done in order to investigate how the spark itself affects the contamination of the electrodes and to see if there is some kind of self cleaning effect. The electrodes used were made of tungsten and of the
kind intended for TIG-welding. The prototypes were named after the chimney they were mounted on, 1 and 2. The active discharge gap on each prototype is called A and the other one B. For example, 2B is the passive discharge gap on prototype 2. The sound emitted from each discharge gap at both prototypes was measured in the lab before and after the test period. The amplitude was measured in a 180° span with 10° increments in random order on the longitudinal plane. The angle 0° was defined as perpendicular to the discharge axis, see fig. 2. The distance between the emitter and receiver was 65cm. At each angle 100 consecutive pulses were measured, synchronized and averaged.

A spark that repeatedly strikes between two points shows a variation in the discharge path between the different discharges. This results in a time jitter on the received acoustic pulses, see fig. 3. In order to calculate the mean value of several pulses they first need to be synchronized in time. This was performed according to the LSE method described in [6]. From the resulting averaged curve the difference between the first local maximum and the first local minimum was defined as the amplitude. When the 100 recorded pulses were synchronized data on the jitter distribution of the time of flight could also be obtained. This variable was also compared before and after the environmental test. The test period lasted for 1.5 months.

2.2 Acoustic performance in expected usage environment

It is not only the transducer itself that needs to be evaluated in rough conditions; the acoustic signals it emits should also be investigated in the same environment. In this test, the electronics around the gap discharge emitter were modified and a receiving part was added. The setup used in section 2.1 only managed to produce spark discharges on a periodic basis since the trigger command were created using a timer circuit. In this test, the electronics used in section 2.1 were integrated with fluid flow electronics that normally work with piezo electric transducers. This new setup used the gap discharge emitter as the sender and a standard 200kHz piezo electric transducer as the receiving part. With this setup it is possible to measure transit times from the gap discharge emitter to the
Figure 3: Example of the time jitter that occurs from several spark discharge acoustic pulses.

Table 1: Gas composition in the test environment.

<table>
<thead>
<tr>
<th>part</th>
<th>proportion (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂</td>
<td>72–76</td>
</tr>
<tr>
<td>O₂</td>
<td>14–20</td>
</tr>
<tr>
<td>CO₂</td>
<td>0–3</td>
</tr>
<tr>
<td>H₂O</td>
<td>5–13</td>
</tr>
</tbody>
</table>

piezo receiver and to test the emitted sound pulses in the same environment as in section 2.1. The emitted sound pulses were recorded on an oscilloscope in order to investigate the waveform. The actual chimneys that were used as the test site had diameters in the range of 1.9–2.9m. The fluid medium in the chimney is basically air at atmospheric pressure, an estimate of the air composition is presented in table 1 and the temperature was <80°C.

3 Results

3.1 Long term environmental test

The visual results from this test can be found in fig. 4. Prototype 2, mounted in chimney 2, was most affected by surface contamination. It was covered with a several-millimeter and up to a centimeter-thick layer of deposited dirt. Prototype 1, mounted in chimney 1 with less moisture, is far less affected by deposits but seems to be more corroded. The electrodes have not suffered any visible corrosion, though. The outcomes from this test were slightly changed during the test period due to malfunctioning electronics. The excitation circuit used proved to be too weak and broke down, and had to undergo repair. This meant that the periodic spark discharges did not occur for approximately 3 weeks.
Figure 4: Gap discharge emitter prototypes as seen after environmental tests, (a) chimney 1 (b) chimney 2

of the test period. This made it more difficult to estimate any self cleaning effect of the electrodes due to spark discharges. On prototype 1 there is no visual difference between 1A and 1B. On prototype 2 there is a visual difference: the electrodes on 2B are clearly more covered with dirt than 2A. Most important, however, is the fact that both discharge gaps on both prototypes worked perfectly when the electronics were repaired.

Fig. 5 presents the measured amplitudes before and after the test period. Due to the problem with the excitation electronics, the measurements on prototype 1 after the test were made with the electronics belonging to prototype 2. This is most likely the reason why the amplitude after was larger than before in figures 2.5(a) and 2.5(b). Although both excitation circuits were built identically, there were still some uncertainties in the electric components and cabling that was not controlled for in this work. It can be concluded, however, that the shape of the radiation pattern for prototype 1 is more or less unchanged in the longitudinal plane. For prototype 2, the identical setup was used before and after and we can see the results in figures 2.5(c) and 2.5(d). In the range of $\pm 50$ degrees the profiles are very similar in shape and the measured amplitudes are actually a little bit stronger after than before. Closer to $\pm 90$ degrees the profile seems to decrease a few dBs after the environmental exposure. Taking into account the heavy deposits on prototype 2, fig. 2.4(b), this is most likely explained by the physical obstruction of the sound by the deposits. The other investigated parameter, the time jitter distribution, is not as unchanged as the amplitude. These measurements show a varying behavior. Prototype 1, which was less affected by deposits, shows that the active part, 1A, is not very affected by the test. The jitter distribution standard deviation $\sigma$ in both cases was
around 1.5μs at 0° going down to <1μs at the sides; see fig. 2.6(a). 1B seems to be more influenced by slightly irregular time stability after the test. σ increases by about 0.5μs at 0° and at most approximately 1.5μs at -30° as seen in fig. 2.6(b). 2A, which was the active discharge gap on the most polluted prototype, is actually showing a general improvement in the time stability where σ decreases from around 1.5μs to 1μs at 0° and is less affected at the sides. 2B seems to be mostly unchanged in the smaller angles but is clearly affected on the sides, where σ increases by approximately 0.5μs. Overall, the jitter distribution standard deviation σ is quite consistent and remains under 2μs in almost all cases. There seems to be a tendency towards slightly more irregular data on the passive electrode gaps, 1B and 2B, after the environmental test.

3.2 Acoustic performance in expected usage environment

In fig. 7, some examples of signal waveforms can be seen. These were all received with a ∼200kHz piezoelectric transducer. The first pulse, 7(a), was recorded in the lab at 2.9m distance between emitter and receiver. It serves as a reference of the signal received in the relatively undisturbed air of the lab environment. The pulse in 7(b) was recorded in a chimney with a diameter of 1.9m, and 7(c) in a chimney with a diameter of 2.9m. The frequency graphs are FFTs of the received signal, calculated on the first 100μs of the received signal.

The worst case was seen in the ∅2.9m chimney but the main reason for this is not, as expected, the longer distance, but instead the lack of alignment between the gap discharge emitter and the piezoelectric receiver. The openings that were available in this chimney turned out to be somewhat misaligned. A piezoelectric receiver is generally

Figure 5: Signal strength from gap discharge emitters before and after exposure to test environment
Figure 6: Time jitter on transit times between gap discharge emitters and piezoreceiver before and after exposure to test environment, and standard deviation $\sigma$ at different angles.

4 Conclusions

The results from the environmental test of the transducer itself indicate that the transducer’s ability to emit sound is basically unaffected. The amplitude of the sound shows no signs of reduction on either the passive or active discharge gaps or between different grades of contamination. The time jitter distribution also seems to remain consistent throughout the test. The emitter tested in chimney 2 was almost entirely covered in quite directional, and if not perfectly aimed towards the acoustic source, there will be a reduction in received signal amplitude. Misalignment experiments later conducted in the lab revealed signal quality very similar to those shown in fig. 7(c), from the 2.9m chimney. The frequency spectrum in 7(c) shows that the major frequency component is around 30kHz, which is much lower than the transducers’ center frequency of $\sim$200kHz. It is also apparent on the pulse with the dominant triangular-shaped wave with lower frequency. This effect is, as discussed above, achieved when the transducer is not aimed straight towards the source and high amplification is used in order to compensate for the loss of signal strength. Since this low frequency seems to be represented in all three graphs in fig. 7, it indicates that the pulse must contain significant energies in this spectrum. The receiving transducer also had a radial resonance frequency of around 30kHz, so the low frequency spectra of the gap discharge pulse did excite the radial mode on the transducer as well.

The commercial flow metering electronics used for pulse detection and time measurements was able to successfully detect over 95% of the transmitted pulses.
dirt depositions, and even though the electrodes were barely visible, it still managed to function with no significant degradation. This shows that gap discharge emitters shows great potential for use in harsh environments.

From the acoustic performance tests, it can be concluded that the signals from a gap discharge emitter are not as regular and predictable as when using the conventional piezo to piezo transition technique for ultrasonic pulses. This requires more processing from the onboard electronics in order to accurately detect any incoming pulses. Although the detection circuit used in this test is normally used in a commercial flow meter system and is in no way adapted for signals from gap discharges, it still managed to detect at least 95% of the pulses and correctly calculate transit times. This was proven both in the lab and in the test environment.

The temperatures in this test only reached a maximum of approximately 80°C so there were no high temperature parameters included in this paper. Since the emitter can be constructed using high-quality metals and ceramics, it can be stated that the emitter itself can easily be upgraded to withstand higher temperatures. The acoustic performance is more likely to be changed with higher temperatures. If the air between the electrodes is heated, it will change the conditions for the electric discharge, and this will have an impact on the created acoustic waves.

The general conclusion is that dust, contamination and moisture are conditions that the gap discharge emitter can tolerate. In these tests, most of the parts used around the gap discharge emitter were standard commercial parts. Therefore, the emitter has
great potential for improvements such as more careful installation at the test site and dedicated electronics custom-made for the purpose.

References


Electric spark discharge as an ultrasound generator in flow measurement situations

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Electric spark discharge as an ultrasound generator in flow measurement situations

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Abstract

In this paper, a different way to create acoustic signals for ultrasonic gas flow measurements is investigated. The aim is to develop an ultrasonic flow meter system that is capable of operation in extreme environments. These environments might consist of extremely high temperatures, moisture, contaminating particles, low gas pressure and large geometries. Traditional ultrasonic transducers are sensitive to these conditions: their performance suffers, or they may even stop functioning if exposed to such environments. The development of new transducer technology is therefore crucial to allow ultrasonic flow measurements in harsh environments. In this paper, the gap discharge emitter is evaluated as a candidate to be used in these applications. Its capabilities as a sound source are investigated, and its impact on flow meter performance is estimated. It can be concluded that, despite the uncertainties it introduces to a flow meter system, it stands out as a strong candidate to be used as an acoustic emitter in a gas flow meter system for extreme environments.

1 Introduction

Ultrasonic measurement technology is, in many ways, a flexible and reliable way of performing measurements. There are no moving parts, and it can be used for non-interfering and non-destructive measurements [1]. The type of transducer that can be used is limited. For a gas flow measurement system, the transducers can, for example, be exposed to very high temperatures, moist condensation or highly contaminating dust particles. Under these circumstances, if traditional ultrasonic gas transducers are used, their performance changes dramatically. It might even prevent operation. High temperature gas transducer technology with promising results have been investigated, [2, 3]. They tested their transducers in exhaust gas from a combustion engine and reported that their transducers should be able to operate at gas temperatures up to 600°C. With added exposure to heavy surface contamination, any transducer, regardless of its temperature durability, that uses a surface to medium acoustic connection is limited.

In this paper, a technique involving an electric gap discharge to create ultrasonic sound waves in air is investigated. This method is a robust way to acquire intense acoustic pulses that can be used in particularly harsh environments. Because it acts independently of acoustic matching between emitter and medium, it is far less sensitive to any contamination. It can also be made of materials that allow exposure to very high
temperatures. One disadvantage is the fact that it only acts as an emitter of acoustic waves. In order to use it in a gas flow meter system, it is dependent upon a receiving unit with matching durability to the harsh environment. The idea in this work is to investigate the properties of an intense and durable sound source for gas flow measurements. If it is found to be suitable for this task, future work will focus on developing a dedicated receiver that can endure in the same environments.

Studies on the acoustic wave that occur after a spark discharge in air have been performed [4, 5, 6]. Studies that investigate their suitability as an ultrasonic emitter for flow measurements seem to be less frequent. In order to use it as an ultrasonic emitter in flow measurement situations, it has to be evaluated for that purpose.

The acoustic pulse emitted from the gap discharge can be evaluated with respect to different properties. Key properties include the sound amplitude, frequency content and the time of flight between transmitter and receiver. In a flow measurement situation, these properties have different impacts on the result. Frequency content and amplitude affect the detectability of the signal. The receiving unit is usually sensitive to a certain frequency band. In this band, the emitted acoustic energy is required to maintain a sufficient amplitude in order to be distinguished from any background noise or other disturbances. The focus in this work is in the ultrasonic frequency domain. The receiving transducer used in this work has a center frequency of ∼200 kHz. Thus, transducer pulses were easily received and should be easily detected by any conventional equipment. No further investigation of frequency content was made outside of this interval. Instead, the focus is to evaluate its suitability in a gas flow meter situation where timing is crucial. There are uncertainties related to the time of flight for sound waves created by a gap discharge. The uncertainties generally derive from two phenomenas: the spatial fluctuations of the spark when consecutively fired between the same locations and the effect of varying spark energy. The spatial fluctuations cause the emitting source to act as if it is moving back and forth and, thus, affects the flow measurement accuracy. The energy content in the spark impacts the speed of the emitted pulse. The acoustic wave emitted from a spark is in the form of a shockwave, as described by Freeman and Craggs [5]. The shock expansion varies with different initial energy levels in the spark, and this affects the overall travel time for the emitted pulse. The above uncertainties must be investigated in order to evaluate the impact they would have on a gas flow meter.

2 Experimental setups

2.1 General setup

The experimental setup consists of two parts: the first is the transmitting part, the electric discharge, and the second is the receiving part. In all described experiments, the receiving part consists of a piezoceramic transducer with a center frequency around 200 kHz. The received signals have been amplified by a panametrics 5052PR and then recorded with an oscilloscope card in a standard PC, see Fig. 1. The main principle in obtaining a spark discharge between two electrodes in air is to create a sufficiently
strong electric field between them. One way to do this is to keep one of them at ground level voltage and apply a large positive or negative voltage at the other. The electric breakdown voltage for air varies with many parameters, but a typical breakdown occurs around $30\, kV/cm$ \cite{7} for spherical electrodes and atmospheric pressure. In this work, the electrodes had sharp points and were made of tungsten, which gave lower breakdown voltages: around $10\, kV$ for an electrode distance $d=10mm$ were observed during experiments. The air gap possesses a very large resistance. Once the spark is initiated, this resistance drops to a fraction of the initial value, and there is a very rapid current growth between the electrodes. The current transient that goes through the spark channel causes an intense heat release. This rapid thermal change causes a sharp rise in pressure, which generates the sonic waves \cite{7}. By storing the discharge energy in a capacitor, the energy of the spark can be controlled.

In this work, two different setups were used to generate spark discharges.

### 2.2 Setup 1 - High voltage capacitor discharge

In this setup (Fig. 2), a high voltage (HV) capacitor is charged by an HV-supply that is capable of producing voltages up to $30\, kV$. The capacitor is connected in parallel with the electrodes that hold the discharge. Charging the capacitor is made through the resistor, $R$. Electric breakdown of the air between the electrodes occurs spontaneously when a sufficient voltage is reached. The capacitor rapidly discharges its stored energy over the spark. $R$ limits the current drawn from the HV-supply to the spark. The capacitors used in this setup have a size of $2\, nF$. To achieve larger capacitances of $4$ and $8\, nF$ they were connected in parallel to reach the desired capacitance.

With this setup it is easy to create discharges with consistent strength because the voltage is controlled directly through the HV-supply. The exact discharge voltage is not, however, decided with high accuracy since the discharge is not triggered or forced to a
certain voltage. The discharge simply sets off spontaneously when sufficient voltage is reached. It is, however, accurate enough to generate pulses with sufficient consistency in order to distinguish whether or not phenomena that occur are related to changes in sound amplitude. The actual discharge gap in this setup (Fig. 3) was designed to be adjustable. It is possible to set the discharge gap, d, and rotate the gap around its radial axis. The electrodes are made of tungsten with a radius of 1 mm and the type normally used for TIG-welding. They are held by blocks of PTFE to isolate them from surrounding parts. The electrode tips used in the experiments have needle-shaped ends.
2.3 Setup 2 - Transformed capacitor discharge

The second kind of excitation circuit is more focused on controlling when the spark occurs. Instead of letting the discharge occur spontaneously, it is triggered on a given command. The circuit, seen in Fig. 4, uses thyristor (Th) to accomplish this. Once the thyristor receives the trigger signal, it closes the circuit and keeps it closed until the current through it falls below a certain threshold. With the circuit closed, the capacitor discharges across the primary side of the transformer, $T_x$, and the voltage on the secondary side rises rapidly until sufficient breakdown voltage is reached. This generates a discharge that is better defined in time than that of setup 1 but at the cost of amplitude consistency in the generated acoustic pulses. Setup 1 will charge until a specified voltage level is reached and the discharge occurs spontaneously at about the same voltage levels each time. With this setup, the discharge is forced to occur, and the circuit will deliver sufficient voltage needed at any instant. Of course, an upper limit on the high voltages that can be delivered exists, but with reasonable values of $d$ the discharge occurs without overloading the circuit. The discharge capacitance used is $10 \mu F$ and is charged using rectified net power and therefore reaches a peak value of approximately 320 volts ($230\sqrt{2}$). The energy stored in the capacitance is equal to:

$$W = \frac{1}{2} CV^2$$  \hspace{1cm} (1)

This means the capacitance in this circuit initially holds an energy of 0.51 joules. The amount that is actually transferred to the spark discharge is not monitored. The transformer used is an ignition coil intended for car ignition systems. It is capable of outputting voltages of up to 60 kv and has a 70:1 turns ratio according to specifications.

With this circuit it is possible to accurately control the occurrence of the spark. Because no high voltage supply is used, the circuit has no need of high voltage rated components and can instead be built using standard electric components.

In this setup, a different discharge gap was used (Fig. 5). This design is a simplified version that cannot be adjusted as easily. It was originally designed to be tested in a real industrial environment and can be seen as a more robust and practical construction. It’s discharge gap is fixed at 10 mm, and the electrodes are axially arranged in a horizontal plane. They are made of the same material as in setup 1: tungsten with a radius of 1 mm. The tips have sharp ends.

3 Experiments

A number of experiments were performed to establish how the spark discharge works as an ultrasonic emitter in a flow meter application. The single most critical factor is transit time stability. Two major causes for time instabilities were investigated: transit time instabilities due to fluctuations in spark discharge path and shock wave phenomena resulting in nonlinear speed of sound for part of the sound path.
3.1 Transit time instabilities due to fluctuations in discharge path

The spark from an electric discharge in gas tends to switch between different paths when being repeatedly fired between the same locations (Fig. 6). This leads to an uncertainty because the emitting source appears to be moving back and forth from the perspective of the receiving side. The aim is to analyze the time jitter caused by this phenomena and how it is affected by discharge length and energy.

In this experiment setup 1 was used to generate discharges with consistent amplitude within each measurement set. The electrode distance, $d$, was varied between 5, 10 and 15mm in order to investigate the influence of different discharge lengths. For these values
of \(d\), the capacitance, \(C\), was set to 4\(\text{nF}\). At a gap distance \(d=10\text{ mm}\) another two sets of measurements were performed with \(C\) set to 2 and 8 \(\text{nF}\). This was done to test the effect of different energies with a constant discharge gap. In each configuration, the resulting acoustic pulse was recorded from 100 consecutive discharges at a distance of 65 cm; an example can be viewed in Fig. 7(a). The collected data was then analyzed and the synchronization jitter, \(\tau\), calculated according to the LSE method described elsewhere [8]. The \(\tau\) parameter contains the time deviation for each pulse relative to the mean deviation for all pulses. \(\tau\) can then be used to estimate the time stability due to the spatial fluctuations of the sparks.

### 3.2 Transit time instabilities due to shock wave phenomena

The amount of energy transferred into acoustic energy during the spark discharge is connected to the amount of electric energy consumed. This affects the behavior of the transmitted acoustic waves [4, 6]. This phenomena affects the speed of sound for the acoustic pulses sent out from the spark. To investigate this, it is necessary to measure the time of flight for pulses that come from discharges with different energies. The easiest way to obtain this is to vary the capacitance, \(C\), which holds the discharge energy. In Section 3.1, data from such measurements is analyzed. Data were collected from setups that used an electrode distance of \(d=10\text{ mm}\) and capacitances of 2, 4 and 8 \(\text{nF}\). To get comparable data, all pulses from each configuration were synchronized with respect to time. This is done using the method described in Section 3.1, and an example of the result from such an operation can be found in Fig. 7(b). The last step is to average all synchronized curves within each setup into a single curve that is then used for comparison.
3.3 Combination of uncertainties in a prototype test circuit

As discussed above, both the initial discharge energy and spatial fluctuations might affect how the transmitted acoustic waves behave. What can we expect from a situation when these phenomena are represented simultaneously? This is the case when using setup 2 because it does not actively regulate the discharge voltage. This kind of discharge excitation is found to have amplitude variations between emitted acoustic pulses when being repeatedly fired with constant parameters. This is due to the stochastic behavior of the breakdown with conditions for electric breakdown changing from one instant to another. This setup estimates how the above-mentioned phenomena act together and their impact on the time stability. It is also suitable to use the results from this experiment to evaluate this kind of excitation circuit. This circuit is more likely to be of the kind that will be used if the gap discharge emitter is used in a flow measurement system.

3.4 Longitudinal plane characteristics

Because the sound from a spark is created directly in the medium, there is no actual directivity of the sound. The spark can be simplified as a line source over short distances and as a spherical source over long distances, [9]. This means it is symmetrical in the radial plane and, thus, should have a symmetric beamform in this plane. In the longitudinal plane, along the spark axis, the spark is not symmetrical and, therefore is suspected to show a varying radiation pattern. Spatial fluctuations are also observed (Fig. 6) and their impact varies with the angle of the view of the receiver. In this experiment, setup 2 is used, and the discharge gap is rotated around the radial axis at different angles \( \alpha \). The investigated angles span from -90 to 90 degrees in 10 degrees increments. 0 degrees is perpendicular to the longitudinal axis of the spark, as seen in Fig. 1.

4 Results

4.1 Transit time instabilities due to fluctuations in discharge path

As mentioned earlier in Section 3.1 a typical measurement performed could give the resulting curves found in Fig. 7(a). The same curves corrected according to the calculated jitter, \( \tau \), can be observed in Fig. 7(b). The interesting information in these measurements is how much jitter is expected in time of flight, whether or not the jitter distribution shows anything and whether or not the spark length and/or energy affects the jitter and jitter distribution.

First, by looking at the histograms in Fig. 9 and the results in Table 2, it can be seen that the discharge energy alone seems to have an obvious impact on the jitter distribution. Higher discharge energy leads to a tighter distribution with a clearly smaller jitter standard deviation. The breakdown voltage was observed to be around \( \sim 8 \text{kV} \) for
Table 1: Time standard deviations with different electrode distances, corresponding to histograms in Fig. 8. $C=4\mu F$

<table>
<thead>
<tr>
<th>d (mm)</th>
<th>$\sigma(\mu s)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.88</td>
</tr>
<tr>
<td>10</td>
<td>0.77</td>
</tr>
<tr>
<td>15</td>
<td>0.73</td>
</tr>
</tbody>
</table>

Table 2: Time standard deviations with different discharge energies, corresponding to histograms in Fig. 9. $d=10\text{mm}$

<table>
<thead>
<tr>
<th>C (nF)</th>
<th>$\sigma(\mu s)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.21</td>
</tr>
<tr>
<td>4</td>
<td>0.77</td>
</tr>
<tr>
<td>8</td>
<td>0.74</td>
</tr>
</tbody>
</table>

d=10 mm, and with the capacitances this would, according to Eq. (1), correspond to energy levels of approximately 0.06, 0.13 and 0.26 joules.

The discharge length also seems to affect the jitter. Intuitively, a longer discharge length, $d$, should give the spark a wider possible space for fluctuations that leads to a larger jitter distribution. By studying the histograms in Fig. 8, it can, however, be seen that the case is the opposite. The jitter distribution tightens with larger $d$, and it is also supported by the calculated standard deviations that can be seen in Table 1.

It is worth mentioning that a larger $d$ also leads to a larger discharge energy, even if the capacitance is kept constant. A larger $d$ requires a higher voltage to reach the dielectric breakdown, and according to Eq. (1), this will lead to a larger amount of stored energy in the capacitance. The breakdown voltages for $d=5$, 10 and 15 mm were observed to lie approximately around 7, 8 and 12.5 kV, respectively. For the 4 nF capacitor, this would correspond to approximately 0.1, 0.13 and 0.31 joule. Further, because the discharge energy obviously affects the jitter, it must also have a part in this case. Overall, it is interesting that a larger discharge gap does not create wider jitter distributions.

4.2 Transit time instabilities due to shock wave phenomena

A comparison between the averaged curves from the analyzed data sets can be found in Fig. 10. As mentioned previously, each curve is an average of 100 consecutively measured and synchronized acoustic pulses. In Table 3 the calculated difference is presented. In the table, the curve representing pulses generated with an 8 nF capacitance is defined to $\Delta T = 0$, and the two others compared to the result. It is obvious that the initial
Figure 7: Example of unsynchronized, (a), and synchronized, (b), incoming signals. In this case the sound waves are inherited from discharges with an electrode distance of 10 mm and a capacitance of 4 nF.

The discharge energy used to create the acoustic pulse significantly impacts the time of flight for pulses in the investigated frequency spectrum. It also appears that the effect is larger among the lower energies. Between 2 and 4 nF the travel time decreases at a rate of 1.74 μs/nF but between 4 and 8 nF at a rate of 1.12 μs/nF. This suggests the presence of a saturation effect. The behavior behind this effect is not investigated further, however. The aim is to study the overall influence of the discharge energy on the time of flight for the emitted pulses, and in this case it is clear that higher energy gives the pulse a shorter time of flight. The breakdown voltage was observed to be approximately 8 kV in this case, when d=10 mm. The 2, 4 and 8 nF capacitances would then, according to Eq. (1),
Figure 8: Time jitter histograms for measurement sets with electrode distance $d = 5$, 10 and 15mm and a constant capacitance at $4 \text{nF}$

Table 3: Difference in time between the averaged curves in Fig. 10.

<table>
<thead>
<tr>
<th>C(nF)</th>
<th>$\Delta t(\mu s)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>7.96</td>
</tr>
<tr>
<td>4</td>
<td>4.49</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
</tr>
</tbody>
</table>

correspond to 0.06, 0.13 and 0.26 joules.

4.3 Combination of uncertainties in a prototype test circuit

In Fig. 11, an example of 100 consecutive pulses using setup 2 is displayed. In this set, the amplitude–time of flight connection can be observed. By studying the first positive peaks of the incoming pulses, it can be seen that the amplitude generally decreases as the time of arrival increases. The effect due to spatial fluctuations is also represented in this set, but it is not as obvious by just studying the graph. Compared to the measurements performed to evaluate the effect of spatial fluctuations alone, it can be stated that the
jitter distribution in this case seems to be slightly larger. As seen in Fig. 12, the distribution is wider, and it is also evident that the standard deviation for the jitter in this case, $\sigma = 1.61 \mu s$, is larger than when spatial fluctuations alone dominate. The effect does not seem to be as big as the results from the experiment in Section 4.2 suggest. The variations in this test are, rather, closer to what can be expected in a setup used in real applications.

Setup 2 provides a typical way to utilize the gap discharge transmitter in ultrasonic flow measurement systems. Although it introduces an extra level of uncertainty it can be stated that it would not introduce any larger errors compared to a circuit with an HV-supply.

4.4 Longitudinal plane characteristics

Recorded amplitudes in Fig. 13 show the difference between the first local maximum and the following local minimum. The local extremes were collected from a curve that was averaged over 100 synchronized pulses. Thus, for each tested angle, 100 pulses were recorded, synchronized and averaged in order to estimate the amplitude. The synchronization jitter from each angle is presented in Fig. 14. The acoustic radiation pattern for the investigated frequencies, approximately 200 kHz, shows that the amplitude of the
Figure 10: Mean value of synchronized pulses with different amplitudes due to varying initial discharge energy. Initial pulse energy is controlled by the capacitor size that holds the electric discharge energy. Transit time is obviously related to initial pulse energy.

Figure 11: Example of measured set with combined uncertainty effects

emitted sound is highest in the direction of the radial axis from the spark. The amplitude, which is amplified 40 dB before reaching the oscilloscope has its maximum value of 1.77 at $\alpha=0$ and then decreases exponentially until it reaches a value of 0.63–0.64 volts at -90 and 90 degrees. This corresponds to a loss of around 9 dB. A loss of only 9 dB is not much compared to traditional transducers, which lose most of their signal strength at only 10-15°.
Figure 12: Histogram of measured set with combined uncertainty effects

Figure 13: Radiation pattern of acoustic amplitude in the longitudinal plane

Figure 14: Standard deviations for jitter pattern of acoustic pulses in the longitudinal plane
In order to put perspective on the results from the experiments, we consider a situation in which a gap discharge transmitter is used in an ultrasonic flow meter application. In an ultrasonic transit time flow meter, the flow is acquired by measuring the time of flight for pulses sent in the flow direction and pulses sent opposite to the flow direction (Fig. 15). The time for a pulse traveling diagonally downstream is calculated according to Eq. (2), and vice-versa for the upstream case (Eq. (3)).

\[
\begin{align*}
t_1 &= \frac{L}{c + V \cos \alpha} \\
t_2 &= \frac{L}{c - V \cos \alpha}
\end{align*}
\]

From Eqs. (2) and (3), the velocity \( V \) can be resolved, which gives Eq. (4). Velocity \( V \) is then the average fluid flow speed along the sound path \( L \).

\[
V = \frac{L}{2 \cos \alpha} \left( \frac{1}{t_1} - \frac{1}{t_2} \right)
\]

The accuracy of the flow meter is thus based on the accuracy of the transmission times that are obtained. In order to decide their impact on the overall uncertainty, a general uncertainty analysis can be performed as described elsewhere [10]. Equation (4) is used as a data reduction equation. The uncertainties for \( \alpha \) and \( L \) are defined as zero in order to get the impact from the timing errors only. The certainty expression then becomes Eq. (5)

\[
\left( \frac{U}{V} \right)^2 = \left( \frac{t_2}{t_1 - t_2} \right)^2 \left( \frac{U_{t_1}}{t_1} \right)^2 + \left( \frac{t_1}{t_2 - t_1} \right)^2 \left( \frac{U_{t_2}}{t_2} \right)^2
\]
where $U/V$ is the overall uncertainty. $\frac{U}{V} \times 100$ is the uncertainty in percentage. The uncertainty magnification factors, $UMF_{t1}$ and $UMF_{t2}$, indicate that, in order to suppress any error sources, it is desirable to maximize $\Delta t$, $|t_1 - t_2|$. By designing the flow meter with a longer acoustic travel path, $L$, this is achieved. Thus, the flow meter is more accurate in larger geometries. Another factor that affects the magnitude of $\Delta t$ is the flow velocity $V$. A faster velocity will give a larger $\Delta t$. To get a worst case scenario, we consider the estimated jitter in Section 4.3 where $\sigma = 1.61\mu s$. This means the 95% confidence interval is $\pm 2\sigma$ or $\pm 3.22\mu s$.

In Fig. 16 a general uncertainty analysis of this case is presented. The uncertainty compared to the flow velocity for different pipe diameters is presented. Alpha is set to 45°. It can be seen that, for the smallest pipe diameter, 0.5 m, it is difficult to achieve reasonable accuracy in the actual flow velocity interval. It reaches under 2% for $V$ approximately 27 m/s. For larger pipe dimensions, however, the accuracy is within reasonable levels with flow velocities of just a few m/s. The best case scenario case would, according to the results in this paper, be when $\sigma=0.73\mu s$, as seen in Table 1. This is represented in Fig. 17. An improvement can be seen that is proportional to the smaller $\sigma$. For a 0.5 m pipe, the uncertainty due to the jitter is 2% at about 12 m/s which is a lot slower than in the worst case scenario. The relative improvement is about the same for the larger pipes, but in actual m/s it is not as dramatic as for the 0.5 m pipe.

There are many ways to improve the measurements. Each transit-time can, for example, be calculated from a number of consecutive discharges instead, and the resulting average will be more accurate. Over shorter distances, when the jitter more greatly impacts accuracy, it is also possible to utilize the results from Section 4.4 and rotate the discharge emitter in the longitudinal plane and, thus, obtain a smaller jitter distribution.
Figure 17: Results from a general uncertainty analysis with different pipe diameters and $\alpha = 45^\circ$. Based on the best case scenario when $2\sigma = 1.46\mu s$.

This will be at the cost of amplitude, but over smaller distances, the demanded amplitude on emitted pulses is smaller. From experiments in Section 4.1, it can be concluded that increasing the amplitude of the emitted sound by increasing the discharge energy and/or the discharge length is also beneficial in order to reduce the time jitter distribution. This is a big advantage because the emitter is more useful in large geometries and, therefore, requires as much energy as possible in the created acoustic pulses.

Another requirement from an acoustic pulse in a flow meter is the signal quality. The received pulse must have properties that allow it to be accurately detected. These properties include frequency content and amplitude. The amplitude must be high enough to distinguish the pulse from the noise in the signal. A spark discharge emits very loud acoustic pulses; Wyber [6] reports peak pressures of about 133dB re 20 $\mu N/m^2$ measured at a distance of 3 m. The frequency content was not thoroughly investigated. It can be stated that the 200kHz transducer managed to receive a significant amount of sound energy. The pulses are well distinguished from the noise and should not cause any detection problems. If other frequencies are desirable, it is possible to use transducers that act in these frequency bands instead. First, of course, the spark must produce enough energy in those frequencies.

6 Conclusion

In this paper, the gap discharge emitter is evaluated as a sound emitter in gas flow meter systems. The main focus was on the jitter phenomena that are introduced by the emitter. The different effects are evaluated alone and combined. The magnitude of the jitter is estimated with different configurations, and it is found that the gap discharge
emitter benefits from parameters that provide higher sound amplitude, which is a strong advantage. This makes it possible to use it in very large geometries where high amplitude pulses are required without losing accuracy.

The variations between different discharge energies found in Section 4.2 are important to consider when designing excitation circuits for gap discharge emitters. If the circuit used cannot maintain constant discharge strength, it will cause greater time of flight variations. Although the variations seen from the experiment results in Section 4.2 seem to be larger than what was observed in Section 4.3, when the introduction of amplitude variations were investigated, they still increase the jitter distribution.

The gap discharge emitter also opens up the use of emitters for other kind of geometries of flow meter equipment. If the symmetry of radiation pattern in the radial plane is used, we have an emitter that is more or less capable of emitting sound in a 360° plane. This means there are possibilities to build multipath flow meter systems with only one emitting source and multiple receivers both upstream and downstream.

A gap discharge emitter can be designed all in high quality metals and ceramics that can endure extremely high temperatures. It is also not dependent upon any acoustic matching when emitting the acoustic energy to the fluid medium. This makes it easier to transmit pulses in low pressure gases and when subjected to heavy surface contamination.

The work presented in this paper shows that, under the correct circumstances, a gap discharge transducer holds great potential to be used in gas flow meter systems with extreme environments.

References


