# Development of focused air-coupled ultrasound velocity profiler for steam jet flow velocity measurement

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The novel air-coupled ultrasonic velocity profiler for steam flow measurement is developed for steam jet flow velocity measurement. The steam jet is produced from the electrical boiler, and the steam pressure is 0.1 MPa G, and the average flow velocities of steam were from 190 to 380 mm/s. The steam flow velocity was measured by the developed system and the vortex flowmeter. The flow velocity measured by the developed system is comparable to the result obtained by the vortex flowmeter The probability of the steam flow measurement by air-coupled ultrasound is revealed.

**Keywords:** Steam, Wetness, Jet, Ultrasonic beam focusing, Droplet.

## 1. Introduction

Steam is widely used in industries such as energy transportation media in thermal power plants and nuclear power plants for the electric generation, but also used in food processing and distillation process in chemical plants. The steam flowrate measurement is essential for industrial facilities because it enables us to visualize the consumption, leakage and stagnation of steam. The steam visualization can save energy and improve the operation efficiency of the plant as well. In small processing plants, the steam is under low pressurized and steam wetness is high. Conventional flowmeter such as the orifice flowmeter and the vortex flowmeter have difficulties in applying in the high wetness condition. Additionally, the invasive flowmeters cause pressure drop that is the loss of energy. Thus, the clamp-on flowmeter was developed because of its strong advantage on such points. Clamp-on flowmeter only needs to be attached on the pipe wall for the flow velocity measurement with nondestructive set-up process [1]. The clamp-on ultrasonic flowmeter based on the tuft method was developed in our group [2]. However, the tuft method is not applicable in high wetness condition, because the ultrasound is attenuated by the condensed droplets in the steam as shown in Fig. 1. This phenomenon disturbs the ultrasound reaching to the sensor. By contrast, the ultrasonic velocity profiler (UVP) can measure the flow velocity by the echo signal from the reflector. The droplets in steam are employed as reflector and the velocity profile of steam can be measured by ultrasound in high wetness condition. However, the acoustic attenuation in steam is much higher than that in water and the sound velocity in steam is lower than that in water. Thus, the air-coupled ultrasonic technique used in nondestructive evaluation field is one of the solutions to overcome this problem [3], [4]. The low frequency air-coupled ultrasound is propagated in the air and then enters into the test body. Since the air-coupled ultrasound has an efficient transmission in the steam, it can be applied at high wetness environment. Thus, the developed measurement system is evaluated by measuring the flow velocity of the steam jet in the condition of high wetness.

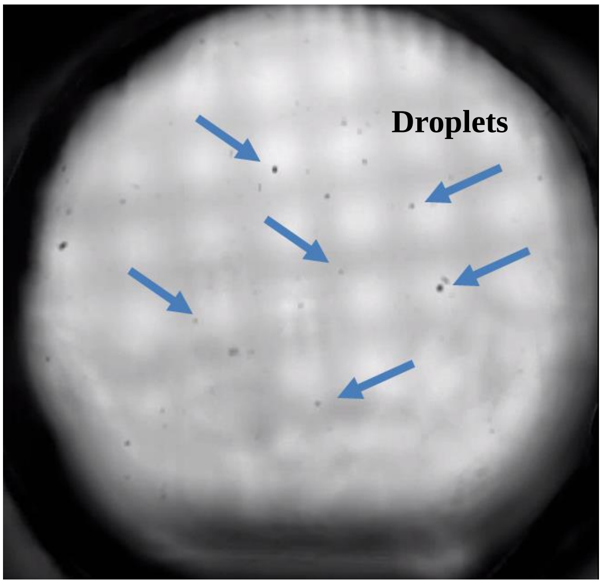



Figure 1: The condensed droplets visualized from the optical window in JIS G 3442, 100 A steam pipe pressurized at 0.3 MPaG.

## 2. UVP system for steam jet measurement

The steam has much lower acoustic impedance than that of water and other liquids. The size of droplets in steam jet is 100 μm ~ 5 mm and the droplets are formed when the wave length of ultrasonic is less than 1 mm. The droplets develop from the outlet. The sound velocity in steam is approximately 473 m/s in atmospheric pressure. Therefore, the ultrasonic frequency is higher than 400 kHz for the wave length which is smaller than droplets. However, since high frequency ultrasound causes attenuation during traveling in the air, the frequency of 400 kHz ultrasound is applied for the steam jet flow measurement in this study. Although 400 kHz is still low frequency compared to the size of droplets, the high intensity ultrasonic beam is required to detect the echo signal from droplets. In order to detect the echo signal from the droplets in steam, the focused ultrasonic beam is employed [5]. The focused ultrasonic beam has high acoustic pressure in the focusing point and high pressure area is widened along the traveling direction of sound.

### 2.1 Focusing sensor

The air-coupled ultrasonic sensor has a matching layer on the surface. Acoustic impedance of the matching layer is about 1.5 M Rayls. The reflection of ultrasonic waves is reduced at the interface between sensor and air, thus, more ultrasonic waves can be transmitted. As shown in Fig. 2, since the sensor has a concave surface to focus ultrasonic beam, the focused ultrasonic beam has high intensity in narrow beam width that enables to detect droplets in steam jet flow. The conventional planar sensor (14 × 20 mm) is shown in Fig. 2 (A). The cross section of the ultrasonic beam of focusing sensor is enlarged to increase the amplitude and SNR of receiving signals.

In order to evaluate the developed focusing sensor, the sound pressure fields of the focusing sensor and the planar sensor were measured. The sound field measurement experiment apparatus is shown in Fig. 3. The apparatus consists of a three axial stage, the receiving sensor, the transmitting sensor, pulsar/receiver, the stage controller and PC with digitizer. The ultrasound is transmitted by the transmitting sensor and received by the receiving sensor that is controlled by the pulsar/receiver. Receiving signals are sent to PC with digitizer and recorded. The measurement position is moved together with the three axes stage controlled by the stage controller. The measurement geometry is 100 × 80 mm in two dimension and 1 mm mesh for each direction. The sound pressure is peak to peak of received signals. The receiving sensor (Japan Probe, 0.4k20 × 14RX) has no damping material to optimize for receiving. The measured sound pressure fields are shown in Fig. 4. The sound field in the planar sensor is 22 mm in width and the beam width is slightly enlarged by propagation in Fig. 4 (a).

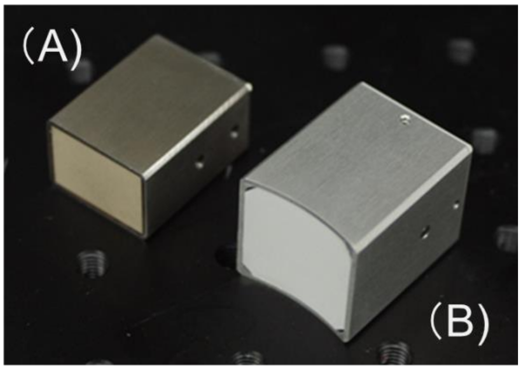



Figure 2: Air-coupled ultrasonic sensors. The conventional planar air-coupled ultrasonic sensor is shown in (A). The developed focusing sensor is shown in (B).

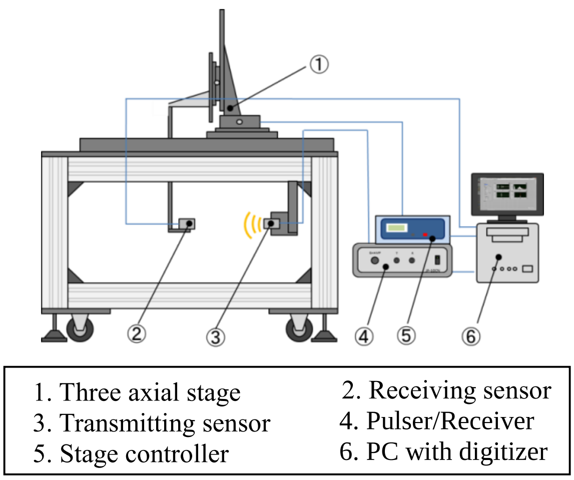
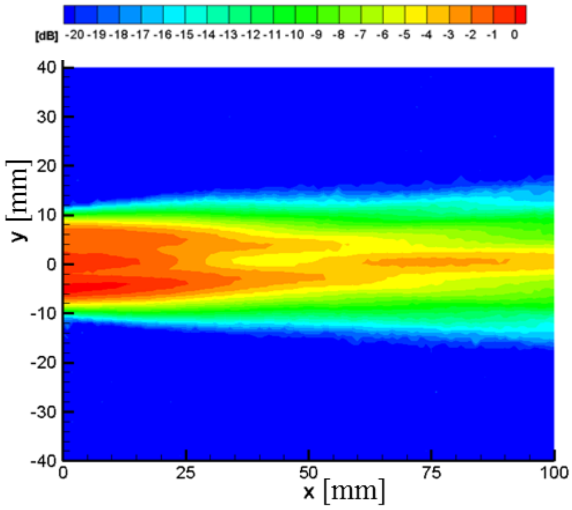
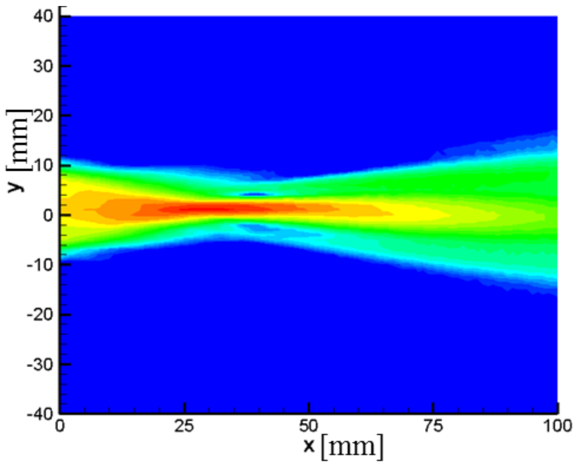



Figure 3: The sound field measurement apparatus. The ultrasonic sensor for evaluation is fixed and emits the ultrasound. Moving the receiving by three axial stage, sensor the sound pressure was detected.




(a) Sound pressure field of the planar sensor




(b) Sound pressure field of the focusing sensor

Figure 4: The measured sound fields by the sound field measurement apparatus. The sound pressure field of conventional planar sensor is shown in (a). The sound pressure field of developed focusing sensor is shown in(b)

The sound field of the focusing sensor is focused on approximate 40 mm point and it has high amplitude compared to the result of the planar sensor at the same point in Fig. 4 (b). The high intensity of ultrasonic beam is located in the focusing point, besides the ultrasonic beam is sharpened to the travelling direction. The higher intensity is located from 25 mm to 60 mm and the beam width is roughly 10 mm. For the steam jet measurement, the ultrasonic focusing sensor was setup to detect the echo signal from droplets in the focusing area.

## 3. Experiment set up

The steam jet flow measurement by developed system is performed. The experiment apparatus is shown in Fig. 5. The pressurized steam is supplied from electrical boiler (MIURA Co, Ltd, ME-50). The pressure limitation was 0.59 MPa, the thermal output was 47.6 kW and the evaporation rate is 76 kg/h. The generated steam is stored in steam header to stabilize the pressure, and then the steam flows through the steam separator DC3S-10 (TLV Co., Ltd.) to remove drain. The steam flow is split into the separator and the bypath which is employed for control the steam flow rate. The steam flowing into bypath is condensed in the heat exchanger (SR-B-1.5, TLV Co., Ltd.). The main steel pipe of the test section is JIS G 3442, 15A SGP white pipe, of which outer diameter was 21.7 mm and the wall thickness was 2.8 mm. Before the test section around 0.5 m of inlet zone which is equal to 20 times of the inner diameter of pipe was prepared ahead of the test section. Vortex flow meter EF73 (TLV Co., Ltd.) was used as reference. The measurement error of the vortex flow meter was less than

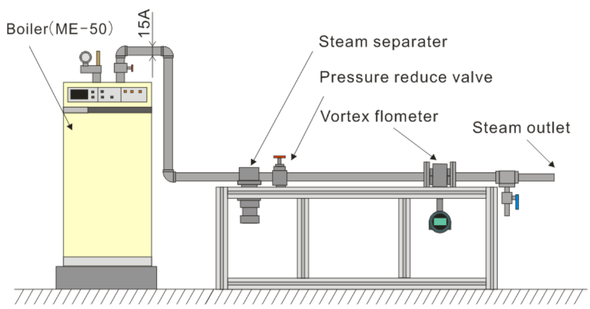



Figure 5: Experimental apparatus for the steam jet flow measurement.

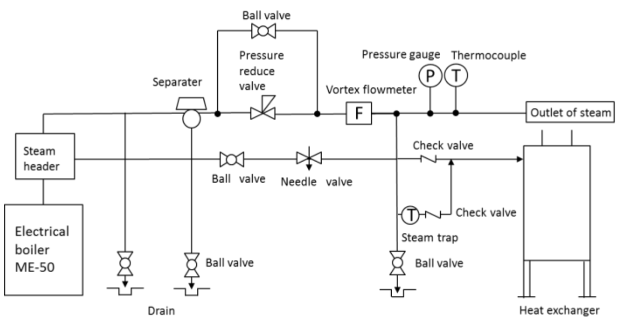



Figure 6: Schematic map of the steam line for the steam jet measurement.

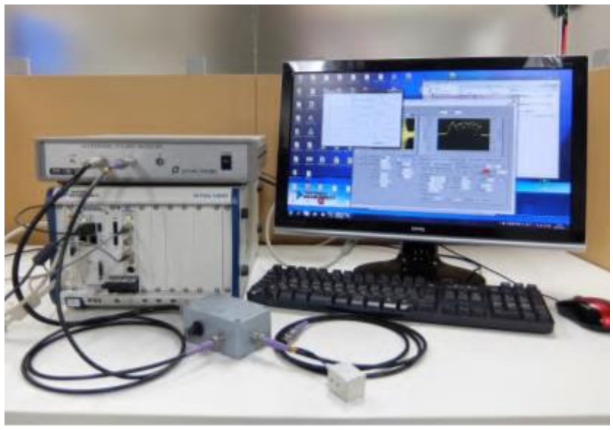


Figure 7: The measurement system developed for the steam jet flow measurement.

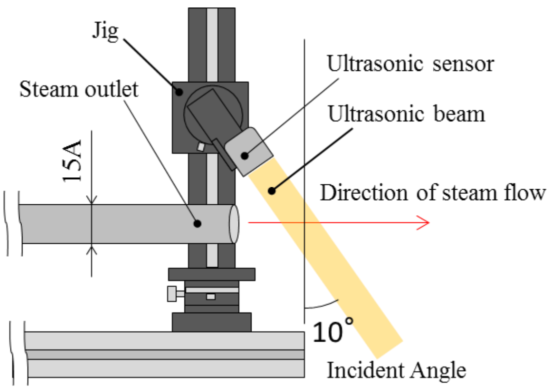
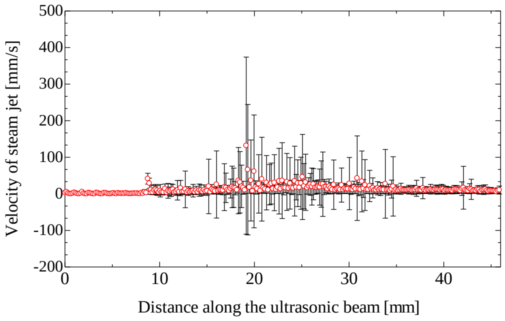



Figure 8: The location of the air-coupled ultrasonic sensor to the steam jet flow.

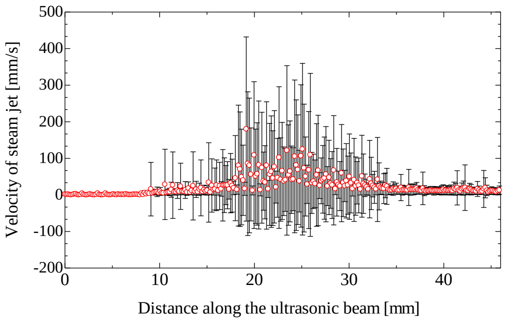
1 % in full scale. The steam pressure was observed by pressure sensor DPH-L113 (Panasonic Corp.). It was reduced to the initial pressure 0.1 MPa by pressure reduced valve DR20-6 (TLV Co., Ltd.). The temperature of steam was 120 °C and the room temperature was 24 °C. The steam pressure was kept to 0.1 MPaG and the steam flow velocity was controlled from 190 to 380 mm/s.

The measurement system is shown in Fig. 7. An Ext-amplifier is applied. Received signals at transducers are low signal-to-noise ratio. The amplifier in the receiver is influenced by noises from power supply circuit. Then, received signals are amplified outside of the receiver before noises generated. The noise filter is in the amplifier. The filter is band pass filter (BPF) that passes a certain band, and removes noise from signals. The ultrasonic sensor is controlled by the pulsar-receiver (JPR-10B, Japan Probe Co., Ltd.). Applied voltage, wave number, frequency, and pulse repetition frequency of the transmitting signal are 110V, 16 cycles, 390 kHz, 2 kHz respectively. The received signal is converted in 8-bit digitizer (NI PXI-5114) with 250 Ms/sec sampling rate. The velocity profile is calculated in personal computer.

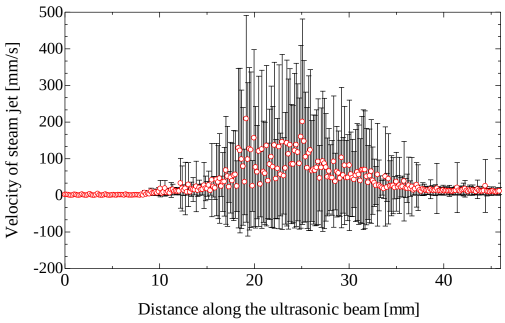
The schematic drawing of focusing sensor is shown in Fig. 8. The ultrasonic sensor is setup with 10 ° incident angle. The location of ultrasonic sensor is setup as the main steam jet which is located between 25 mm and 60 mm from the focusing sensor.



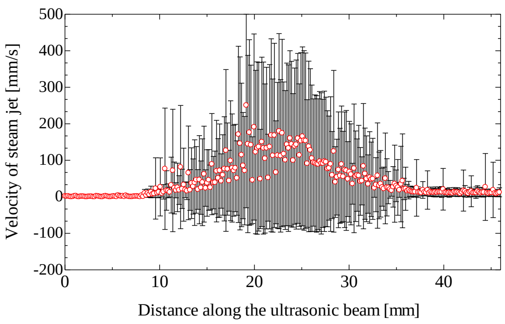

(a) Velocity profile when the average flow velocity measured by the vortex flowmeter was 190 mm/s




(b) Velocity profile when the average flow velocity measured by the vortex flowmeter was 250 mm/s




(c) Velocity profile when the average flow velocity measured by the vortex flowmeter was 330 mm/s




(d) Velocity profile when the average flow velocity measured by the vortex flowmeter was 380 mm/s

Figure 9: Velocity profile of the steam jet measured by air-coupled ultrasonic velocity profiler. The horizontal axis shows the distance from the sensor and vertical axis means the velocity. The plots show the velocity measured by developed system.

## 4. Result and discussion

The results of the velocity profile measured by developed focused ultrasonic steam flow velocity profiler were shown in Fig. 9. The averaged velocity with 10,000 profiles shows the flow velocity of the main steam jet from the outlet. The error bar denotes the standard deviation of each velocity. The main steam jet is observed from 10 mm to 35 mm according to the plots shown in Fig. 9 (b), (c) and (d). The size of main steam jet is developed as 25 mm from the outlet whose inner diameter is 15 mm. The velocities of steam jet increased with the flowrate, and the observed velocity boundary layers were around 15 mm and 30 mm. Moreover, vortexes along the main steam jet are observed in high standard deviations around 18 mm and 25 mm. The sub flow flowing into the main steam jet is observed beyond the vortexes. Hence, the focusing sensor has high intensity of ultrasonic beam in the main steam jet, and the echo signal from the droplets can be detected. However, the measurement error was occurred in the 20 mm because the ultrasonic beam is spread in 20 mm form the sensor surface. The beam spreading causes the larger spatial resolution.

## 5. Summary

The novel air-coupled ultrasonic velocity profiler for steam flow measurement is developed. An air-coupled ultrasonic sensor for steam flow measurement was developed. The air-coupled ultrasonic sensor has a matching layer to reduce the acoustic reflection between sensor and the air. In addition, it has a concave surface to focus ultrasonic beam. Since the focused ultrasonic beam has high intensity in narrow beam width, this enables us to detect droplets in steam by using it. For the demonstration of steam jet measurement, steam jet flow was measured by ultrasonic velocity profiler with the developed ultrasonic focusing sensor. The steam jet is produced from the electrical boiler, and the steam pressure is 0.1 MPa G. The steam flow rate was measured by the developed system and the vortex flowmeter. The flow velocity measured by the developed system is comparable to the result obtained by the vortex flowmeter. Thus, the capability of the steam flow measurement by air-coupled ultrasound is revealed.

## References

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