SUPERSONIC FLOW MEASUREMENT WITHIN A LOW-PRESSURE AREA

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Abstract: The goal of this paper is to describe the idea of measuring a supersonic gas flow within low-pressure areas in order to describe its behavior and to compare the measurement data with the generally described supersonic gas flow behavior derived from its behavior within high-pressure areas. This data should help to make low-pressure supersonic flow simulations more accurate.

Keywords: ANSYS Fluent, ANSYS Mechanics, Optical methods, Pitot tube, Pressure measurement, Shockwave, Solidworks, Thermography,

1 INTRODUCTION

Nowadays when simulating a supersonic gas flow within a low-pressure area, the constants used for calculations are approximated from their trends calculated in high-pressure areas. These constants can be inaccurate, considering the gas flow within a low-pressure area behaves differently than within a high-pressure area. This is caused by the change of a continuous gas flow into a discrete flow of individual gas particles because of the lack of them within the flow.

To be able to describe the behavior of this supersonic gas flow, it is suitable to measure its character with more than one method.

This paper aims at using more methods at once to describe the character of a supersonic gas flow within a low-pressure area. To be able to implement those methods, new measurement chamber has been developed. This chamber allows to implement these measurement methods:

- Application of an optical Schlieren method to visualize the shape of the flow in visible,
- Dynamic pressure measurement and flow’s velocity calculation using Pitot tube,
- Oblique shockwave angle analysis using cone needle to calculate the flow’s velocity and pressure loss behind the oblique shockwave,
- Temperature measurement using IR camera and thermocouple,
- Static pressure and pressure difference measurement within and outside the supersonic flow using deformation pressure sensor.

This paper contains the description of some of the principles of measurements feasible on the new measurement chamber.

2 SUPERSONIC GAS FLOW CHARACTER MAPPING

To fully understand and describe the supersonic gas flow in low-pressure areas, the new chamber allows to perform more types of measurement to complement each other, than its previous version. These are some of the methods applied:

2.1 OPTICAL SCHLIEREN METHOD

This method is based on the change of refraction index of a fluid caused by the change of its density. Any pressure disturbance within the fluid will deflect the light beam that goes through the fluid from its original path at angle depending on the new refraction index of the pressure disturbance. This principle can be described with Clausius-Mosotti equation:

$$n - 1 = K\rho \tag{1}$$

where n [-] is the refractive index, ρ [kg·m^{-3}] is the densify of fluid and K [m^3·kg^{-1}] is the Gladston-Dale constant (refractivity) of the fluid [1].

Dispersed light beams will be cut off with an optical knife behind the measured disturbance, leaving the picture of a first derivation of density of the measured fluid on a photographic device. The figure 1 shows the schematic layout of the Schlieren method:

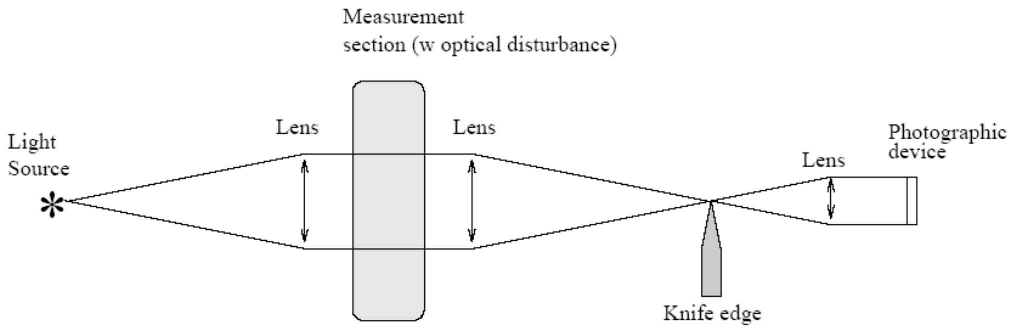

Figure 1: Optical Schlieren method scheme

2.2 PITOT TUBE

Next method applied in the new chamber is the dynamic pressure measuring Pitot tube. Output data from Pitot tube can also be used for calculations of velocity of the flow on its central axis [2]. Figure 2 shows the principle scheme of the Pitot tube:

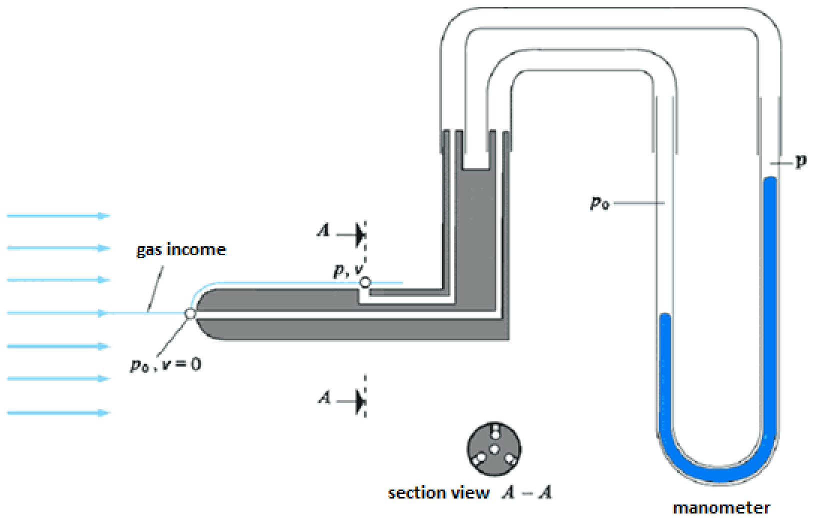

Figure 2: Pitot tube scheme

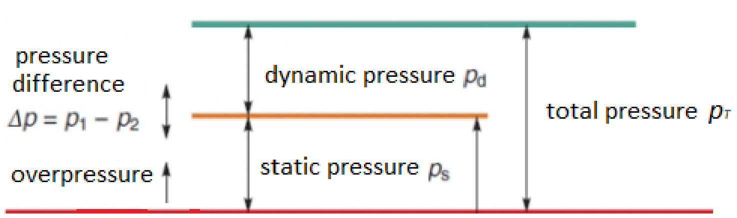

Figure 3: Pressure sections in Pitot tube

In our case the mathematical model used for velocity calculations from measured pressure using the Pitot tube varies in different flow mode:

- Incompressible mode
- Subsonic compressible mode
- Supersonic compressible mode

The gas flow can be considered incompressible when its velocity is lower than 30 % of the velocity of sound. When considering incompressible gas flow, the velocity equals:

$$v = \sqrt{\frac{2(P_t - P_s)}{\rho}} \tag{2}$$

where P_t [Pa] is the total pressure, P_s [Pa] is the static pressure and ρ [kg·m^{-3}] is the density of the gas.

When the velocity of the flow exceeds 30 % of the velocity of sound, it has to be dealt with as with a compressible fluid. The calculation of the velocity of the flow has to consider the Poisson constant and the final equation will be:

$$v = \sqrt{\frac{2\gamma}{\gamma-1}\frac{p_s}{\rho_s}\left[\left(\frac{p_{st}}{p_s}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \tag{3}$$

where γ [-] is Poisson constant, p_s [Pa] is static pressure, p_{st} [Pa] is stagnation (Pitot) pressure and ρ_s [kg·m^{-3}] is the density of the fluid within a static pressure area.

2.3 OBLIQUE SHOCKWAVE ANGLE ANALYSIS USING CONE NEEDLE

A shockwave forms in front of the head of the Pitot tube, when considering supersonic compressible gas flow. Depending on the velocity of the flow and the peak angle of the cone-like Pitot tube the shockwave forms either as the oblique shockwave or the bow shockwave. Behind the oblique shockwave, there is not such pressure loss as behind the bow shockwave, which would distort the pressure and temperature measurement. To find the boundary between the oblique and bow shockwave forming in low pressure areas, more measurements will be performed including different cone peak angles and flow velocities. Next figure describes the relation between the shockwave's shape, the cone peak angle and the velocity of the flow [3].

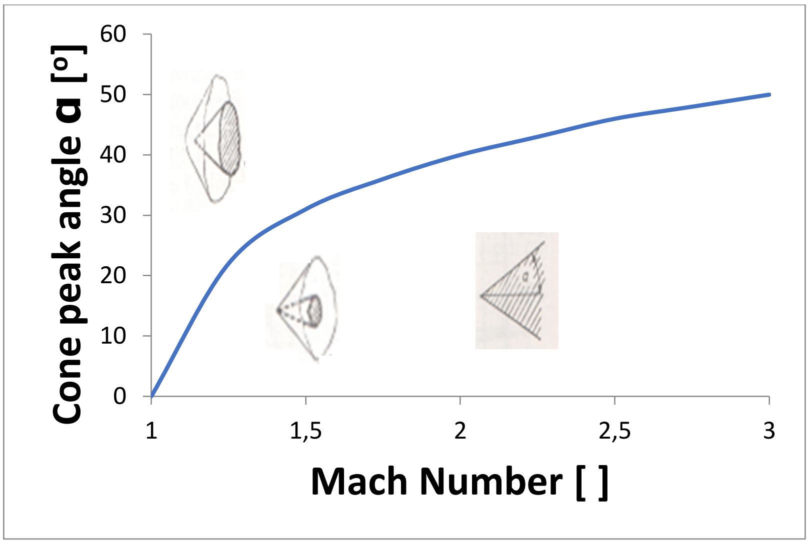

Figure 4: Relation between the shockwave's shape, the cone peak angle and the flow's velocity

3 MEASUREMENT CHAMBER

The base shape of the new experimental measurement chamber is a 20 cm tall cylinder with a 13 cm diameter and a 2,5 cm thick wall. It was designed using modelling and simulation software SolidWorks, all flexible parts were designed and calculated in software ANSYS Mechanics and gas flow simulations were calculated in ANSYS Fluent. All parts of the chamber are designed to be made from steel (including spring steel pressure measuring membrane) except observation apertures which are made from quartz glass in order to let IR and UV light through. Next figure shows a section view of the simplified design of the new chamber with respect to the authorship of the design.

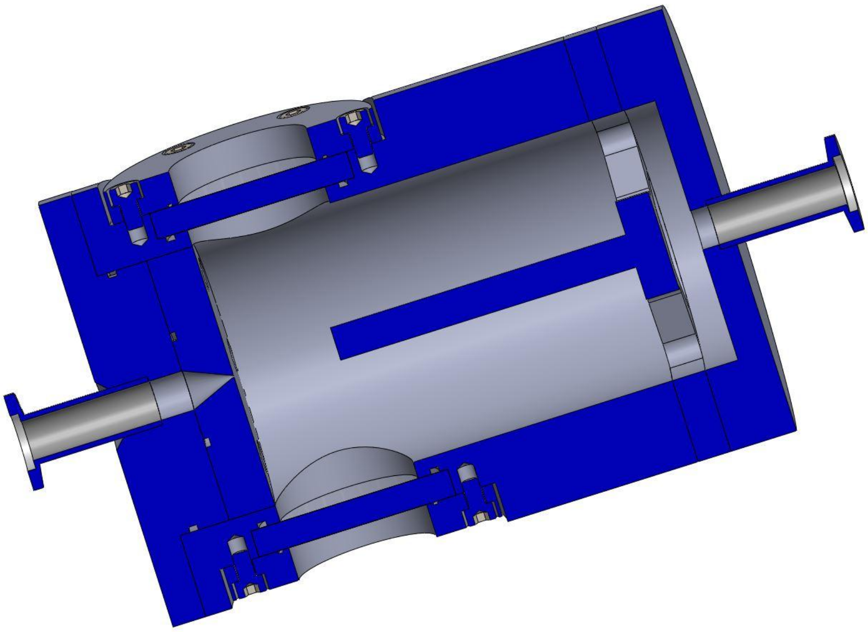

Figure 5: Simplified design of the new experimental chamber

Last figure shows simulation results of a spring steel membrane deformation on the boundary of an input pressure 2 kPa and a working pressure 50 Pa. This membrane will serve as a holder for a strain gauge, which has a limited relative prolongation ± 2,5 ‰.

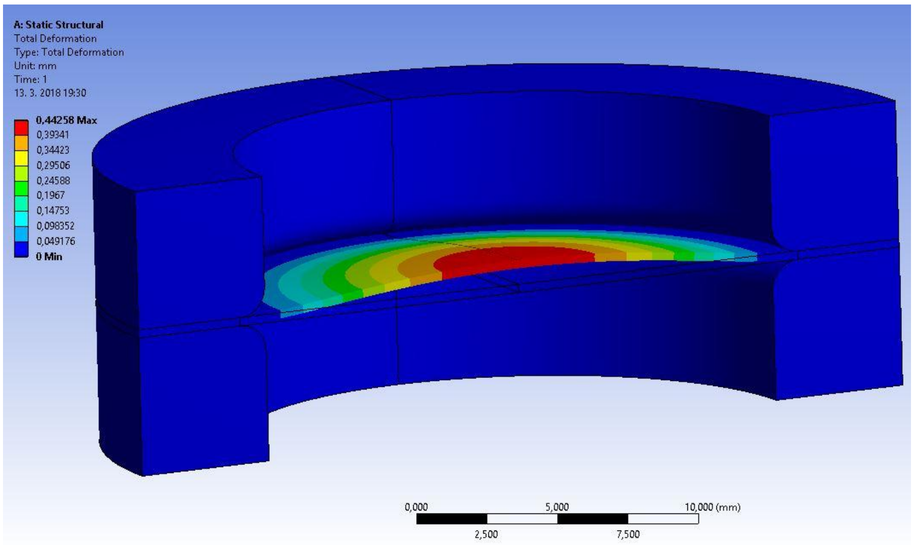

Figure 6: Steel membrane deformation calculation results

4 CONCLUSION

In order to increase the accuracy of measured data, a new experimental chamber was designed. This chamber allows to apply more measurement methods, including optical methods for density measurements, thermocouple sensors for temperature measurements, Pitot tube for static pressure measurements within the supersonic flow, strain gauge for pressure measurements in addition to the Pitot tube and shockwave analysis using combination of a cone needle and optical methods for velocity measurements.

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