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Theoretical and Experimental Characterization of Turbulent Heat Transfer in Compressible Flows

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In this project, we have developed a nano-scale fast thermal anemometry probe to be used in supersonic and hypersonic conditions. The sensor is based on silicon and is manufactured using semiconductor manufacturing techniques. We have characterized how the heat transfer is altered due to the miniaturization and how this can be used to significantly simplify calibration and data analysis. Specifically, it was shown that the relationship between the Nusselt number and the Reynolds number is linear when the sensor is miniaturized, and we have further shown that this is due to slip-conditions. The new sensor was used in a high-speed wind tunnel and compared conventional hot-wires and to Particle Image Velocimetry (PIV).

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Final Report for FA9550-16-1-0170

Theoretical and Experimental Characterization of Turbulent Heat Transfer in Compressible Flows

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Abstract:

In this project, we have developed a nano-scale fast thermal anemometry probe to be used in supersonic and hypersonic conditions. The sensor is based on silicon and is manufactured using semiconductor manufacturing techniques. We have characterized how the heat transfer is altered due to the miniaturization and how this can be used to significantly simplify calibration and data analysis. Specifically, it was shown that the relationship between the Nusselt number and the Reynolds number is linear when the sensor is miniaturized, and we have further shown that this is due to slip-conditions. The new sensor was used in a high-speed wind tunnel and compared conventional hot-wires and to Particle Image Velocimetry (PIV).

Final Report:

The dynamics of velocity fluctuations in incompressible shear turbulence are immensely complex given the highly multi-scale and non-linear nature of the problem. In the compressible flow regime, like in supersonic and hypersonic boundary layers or wake flows, the problem is further compounded by turbulent fluctuations in temperature and density fields in addition to velocity fluctuations, and their coupling. Thus, it is perhaps not surprising that relatively limited progress has been made in studies of compressible shear flows in comparison with their incompressible counterparts. Given the numerous relevant aerospace engineering applications, particularly with regard to space transportation systems, there is a clear motivation to make research progress at a fundamental level in the area of compressible shear turbulence.

Well-refined experimental data is a key requirement for advancing our theoretical understanding in such flow configurations, and also in aiding model development for computational studies and their subsequent validation. The challenging flow environment and short time scales encountered at supersonic conditions typically restrict the ability to acquire experimental data that fully resolves the physical quantities of interest. In recent times, PIV has been employed as the main tool in experimental investigations of high-speed flows; PIV can provide instantaneous flow fields (velocity vectors over a set spatial domain) and also turbulence statistics in a measurement plane or volume. However, current PIV techniques are limited in their spatial and temporal resolution and lack the ability to resolve the full turbulence spectrum. Hence, point measurements that are fully resolved in the temporal domain would greatly complement PIV.

With this motivation, we have adapted a novel nano-scale thermal anemometry sensor for measurements in compressible flows as part of this project. The probe design builds on previous development efforts at Princeton University in the area of nano-scale measurement devices for incompressible flows. The sensors were fabricated in-house using well-established semiconductor and MEMS manufacturing methods. They operate on the same physical principle as a conventional hot-/cold-wire -- the flow condition is informed by changes in voltage or electrical resistance of a small current-carrying wire element that is exposed to the flow. Relative to a conventional hot-/cold-wire, the reduced size and thermal inertia of a nano-scale sensor greatly improves its spatio-temporal resolution, which makes it particularly well-suited for application in a supersonic flow setting. For the first time, we adapt the probe design for measurements in high-subsonic and supersonic conditions.

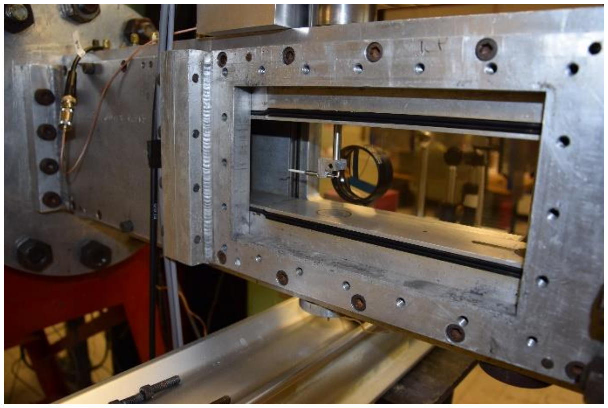
As its name suggests, the nano-scale thermal anemometry probe (NSTAP) is a thermal based sensor capable of accurately measuring flow velocity. Due to its miniature size (sensing element is 60 μm long, 2 μm wide and 100 nm thick), the sensor was shown to have an unparalleled frequency response compared to other conventional hot-wires (Bailey et al. 2010). It was therefore a natural progression for this sensor to be used in compressible flows where the time scales are short and the demand for fully resolved turbulence measurements is high. However, the flow conditions such a sensor needs to encounter are much more challenging than the ones it had previously been tested in. As such, much of this project involved design and testing of improved versions of the sensor to survive the shockwaves still delivering accurate measurements.

<u>Refurbishing Princeton's *M*=3 wind tunnel</u>

It was imperative to refurbish Princeton University's *M*=3 blowdown tunnel before performing tests with the current NSTAP. Due to a halt in supersonic flow research, this facility had not been used for many years. In order for the wind tunnel to be deemed safe to operate, it was completely taken apart; O-rings were replaced and valves were tested and replaced when necessary. The wind tunnel was then reassembled and tested. A traverse mechanism was purchased, a mount for the probe was designed and a Schlieren imaging system was set up. Lastly, sensors were mounted in the tunnel in order to read the static pressure as well as the total pressure and temperature.

Upon refurbishment of the tunnel, the same NSTAP version previously used in subsonic flows was tested, for the first time, in compressible flows. Although the sensor *sometimes* withstood the high loading from high Mach number subsonic flows, it never survived the transition to supersonic, with highly unsteady flow conditions. This confirmed the need to redesign the NSTAP.

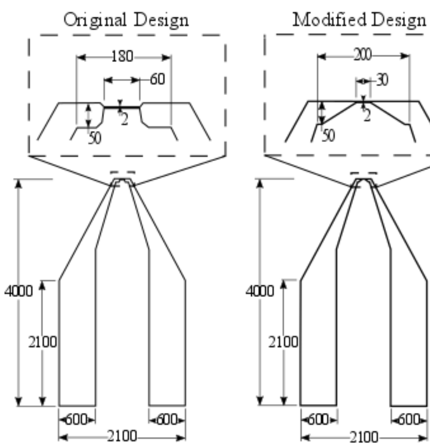
Section of de Laval Nozzle in *M*=3 Tunnel



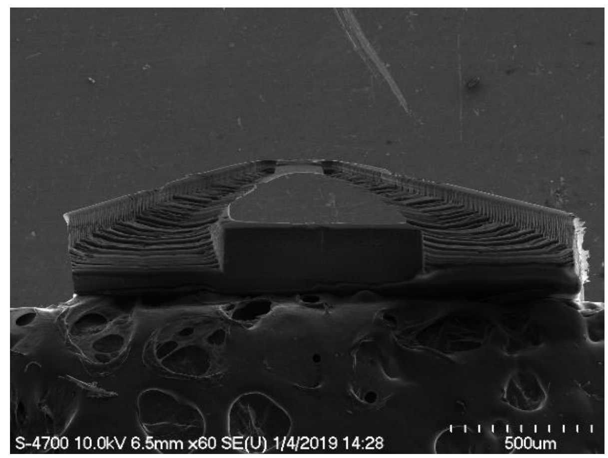
Sensor Mounted in Test Section

Redesigning the NSTAP for supersonic flow applications

Extensive work in Princeton's micro-/nano-fabrication laboratory was performed to make the NSTAP suitable for supersonic flow applications. Among other changes, the two-dimensional pattern of the metallic layer was modified. This allowed the sensor to be as aerodynamic as possible allowing the shock wave structures to avoid the sensing element. New recipes were fashioned to test various metals as well as their deposited thickness. Different etching recipes were also investigated in order for a thin layer of silicon to remain and support the sensing element. Some sensors were tested with a silicon bridge placed downstream of the freestanding sensing element, while others had a thin layer of silicon attached right below the wire. The final sensor was made of platinum due to its attractive electrical and chemical properties. Its sensing element was shorter and thicker than the original one (30 μm long, 2 μm wide and 400 nm thick) and was sometimes supported by silicon in order to reduce vibration and wire breakage.



Two-Dimensional Layout of Metallic Pattern



Scanning Electron Microscope Image of Newly Redesigned NSTAP (extracted from Kokmanian et al. 2019)

Testing the newly designed NSTAP in *M*=2 flow

Once the sensor was redesigned and manufactured, a collaboration was initiated between Princeton University and Bundeswehr University Munich as part of the TRR40 Collaborative Research Center. The primary objective was to test the newly redesigned NSTAP in a supersonic boundary layer to extract highly resolved mass flux measurements and compare the latter to previously taken PIV data. However, due to both time and design limitations, the sensor was mainly placed in the freestream of the Trisonic Wind Tunnel Munich (TWM), which served well for testing the sensor but only limited boundary layer measurements were conducted. The TWM is a two-throat blowdown tunnel capable of varying both the Mach and Reynolds numbers independently and in real-time ($0.2<M<3$ and 5E6 $m^{-1}<Re<$80E6 m^{-1}). This is an attractive feature as it allows for a softer start up flow. The sensor was successfully calibrated in various compressible flows ($0.3<M<2$) and variables such as the turbulence intensity, the integral time scale and the Taylor microscale were computed. Preliminary mass flux measurements as well as wall pressure correlations in a M=0.8 turbulent boundary layer were made.

Two interesting discoveries that arose from the first collaborative campaign were (1) that the turbulence intensity trends appeared to differ significantly between recent data collected with the NSTAP and previous PIV measurements made by researchers at Bundeswehr University Munich. It was first believed that the discrepancies were caused by the difference in physical quantities being measured; while PIV measures velocity fluctuations, a hot-wire operated in compressible flows inevitably measures mass flux fluctuations (the product of velocity and density). Since pressure, hence density, measurements were taken during the campaign, it was possible to include the effect of density fluctuations in the calculation of the turbulence intensity. Given that the corrected data sets did not collapse, i.e. the turbulence intensity appears to decrease with M in the PIV data (see Scharnowski et al. (2019) while the newly taken data does not corroborate this trend, it was believed that an additional effect was causing this discrepancy and that more data would be needed to understand these contradictory trends. (2) Since the NSTAP had not previously been tested in supersonic flows, it was important to understand its heat transfer characteristics in flows traveling faster than the speed of sound. Calibration techniques for conventional hot-wires were used as a baseline (Kovasznay 1950, Smits et al. 1983), however the NSTAP appeared to exhibit a linear Nusselt number dependence on Reynolds number at M=2 which is in stark contrast to traditional hot-wires. Due to these findings, we decided to return to Germany and take more measurements to further investigate. Multiple tests were conducted which allowed us to, in depth, investigate the observations from the first campaign. Tests were performed with conventional hot-wires (Dantec Dynamics) and several versions of the NSTAP with the ultimate goal to enable a better understanding of heat transfer characteristics of the NSTAP both to the flow and within the solid materials. The main conclusions were that PIV and hot-wires indeed had different trends, and that accurately determining turbulence intensities from PIV data is a challenging task. It was further concluded that the conventional hot-wire had severe resonance peaks affecting the data at around 10kHz (previously reported by Hutchins et al. 2015) whereas the NSTAP significantly reduced those effects. By testing different NSTAP designs, the substrate heat transfer could be probed and the heat transfer characteristics modeled. This has the potential to yield sensors that are much more robust that the NSTAP yet similar (or even higher) bandwidth.

These tests also enabled an accurate investigation of the heat transfer characteristic from the sensor to the high speed flow. Several important findings It was found that an increase in overheat ratio in supersonic flows causes a decrease in the Nusselt number. This was also noticed by Kovasznay (1950). The Nusselt number again varied linearly with Reynolds number. Interestingly, it was shown by Stalder et al. (1951) and Stalder et al. (1952) that a transverse cylinder exhibits a linear *Nu-Re* dependence in free-molecule flow. Oppenheim (1953) later generalized the theory for various geometries, including flat plates, and noticed a similar dependence on the heat transfer. Indeed, as the Knudsen number increases, the *Nu-Re* dependence shifts from the well-known 0.5 power law to a linear fit. Given the small length scales of the sensor seen by the fluid flow, it is believed that the NSTAP is operating in slip flow conditions which affects the heat transfer governing the sensor in supersonic and hypersonic flows. A detailed explanation of the aforementioned tests can be found in Kokmanian et al. (2019).

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