WELL RESOLVED MEASUREMENTS OF THE TURBULENT FLUXES IN THE ATMOSPHERIC SURFACE LAYER

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Abstract A new fast-response humidity sensor has been designed, manufactured and evaluated. The new sensor is based on the NSTAP, which is a miniature hot-wire used to measure small scale velocity fluctuations. It is manufactured in-house using semiconductor manufacturing techniques, with resulting high flexibility in the process for optimization to different measurement conditions. It is shown that the sensor has high sensitivity to humidity, yet low sensitivity to velocity. In combination with conventional hot-wires these new sensors will allow for detailed investigation of the scaling of the latent heat flux in the atmospheric boundary layer.

TURBULENT HEAT FLUXES IN THE ATMOSPHERE

Atmospheric turbulence is characterized by extremely high Reynolds numbers, which implies a very large range of scales present in the flow. The largest scales are on the order of 1 km and the smallest on the order of 1 mm. Conducting experiments in such conditions is very complicated since all scales need to be resolved. This implies long sample times, at high sample rates using small sensors. The size of the sensor needs to be on the order of the smallest scales, or smaller, and the bandwidth needs to be higher than the frequency corresponding to that of the smallest eddies. A windy day the wind speed typically is 10 m/s which, according to Taylor's frozen field hypothesis, will result in frequencies up to 10 kHz. Traditionally the bandwidth for sensors used in the atmosphere are much lower than that, but efforts have been made to resolve the complete frequency spectrum for the turbulent velocity field with fast-response velocity sensors, that can survive the rough conditions they are exposed to in the atmosphere [5].

In order to accurately predict the energy balance at the earth's surface—a critical component to any weather prediction or climate model—one needs information about the scalar fields in addition to the velocity field. The scalar fields of interest are mainly temperature and humidity, since those constitute the main contributions of heat fluxes away from the surface due to the atmospheric flow. The sensible heat flux is the covariance between the temperature field and the velocity component normal to the surface, $\overline{w'\theta'}$, which corresponds to the energy transferred away from the surface, in form of temperature. The latent heat flux is the covariance between the same velocity component and the humidity field, $\overline{w'q'}$, which is the part of the energy carried into the atmosphere by evaporation of water at the surface. The ability to predict these fluxes will allow closure to the governing equations, which is the purpose of turbulence models.

Unfortunately, the two covariances are very challenging to measure experimentally, and numerically we can only solve the equations for very low Reynolds numbers. Methods for measuring turbulent velocities and temperature fluctuations accurately are available, but measuring both parameters simultaneously in a measurement volume smaller than the smallest eddies is still a challenge. The available techniques for measuring humidity are neither fast nor small enough to capture small scale turbulent fluctuations. Therefore, there is an acute need for a fast-response, small-size, humidity sensor that can be used in the field. For this purpose, we are currently developing such a sensor at Princeton University.

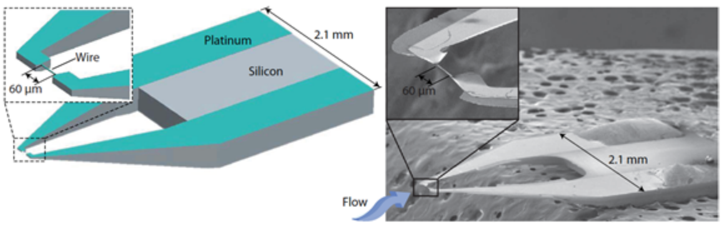

Figure 1. Left: schematic drawing of an NSTAP. Right: Scanning electron microscope image of an NSTAP.

FAST-RESPONSE HUMIDITY SENSOR

The new humidity sensor is based on the Nano Scale Thermal Anemometry Probe (NSTAP), shown in figure 1. The NSTAP is a sensor developed at Princeton University which can measure very small scale turbulent velocity fluctuations [1, 7]. The platinum sensing element of the NSTAP measures 0.1 x 2 x 60 μm. The NSTAP has proven extremely useful in the study of turbulence in laboratory environment [2], due to its miniature size and extremely high bandwidth. What makes the NSTAP technology very attractive for atmospheric measurements is the high degree of flexibility in the design and manufacturing process. Sensors can easily be customized to meet the requirements in terms of spatial and temporal resolution, for a low cost.

Two methods are commonly used to measure humidity in the air: laser based and capacitance based sensors. We recognize that a fast response laser based system will be too expensive to densely instrument test sites (even the conventional slow response systems are very expensive), and the capacitance method will always have a time response several order of magnitudes too slow, since it takes time to replenish the cavity between the electrodes. Another method to measure humidity, is to measure the thermal conductivity of the air, which is a function of humidity. Sensors based on this technique have been tested and shown to work well [3, 4, 6]. Unfortunately, distinguishing the sensitivity of humidity from that of velocity is difficult using this method, since both act to increase the heat transfer from a heated element. During the development process of the NSTAP, it was noticed that the sensor became less sensitive to velocity fluctuations as it was further miniaturized. This effect was due to low Peclet number, which implies that the heat convected is less than that conducted to the air. It was shown that the Peclet number has to be greater than unity in order to be sensitive to velocity changes [1].

This effect can be used to decrease the sensitivity to velocity. A low Peclet number can be guaranteed by further reducing the width of the wire used in the NSTAP. A thinner NSTAP, with a cross-section measuring 100×100 nm was manufactured using electron beam lithography. Preliminary results using this ultra-thin version of the NSTAP in a wind tunnel, indicates that it is insensitive to velocities up to about 10 m/s. However, the wire will still be sensitive to humidity fluctuations since they will affect the molecular heat diffusivity of air.

By keeping the platinum sensing element at a constant temperature, using a circuit similar to those used for constant temperature hot-wire anemometry, the required instantaneous voltage over the wire will depend on the thermal conductivity of the air surrounding the wire, which allows for fast response humidity measurements. Preliminary tests, conducted in an in-house humidity chamber, show that NSTAPs are sensitive to changes in humidity with a promising signal to noise ratio (see figure 2). The preliminary tests are conducted such that the humidity is changed in steps and the sensor output compared to the output from conventional, slow response, sensors. Further tests will be conducted where the new sensor will be compared to laser based sensors both in a controlled environment and in the field. In order to measure both sensible and latent heat flux using a single sensor, the new humidity sensor element can be combined with a regular NSTAP sensing element on one probe which will allow simulatenous measurements of velocity, temperature and humidity.

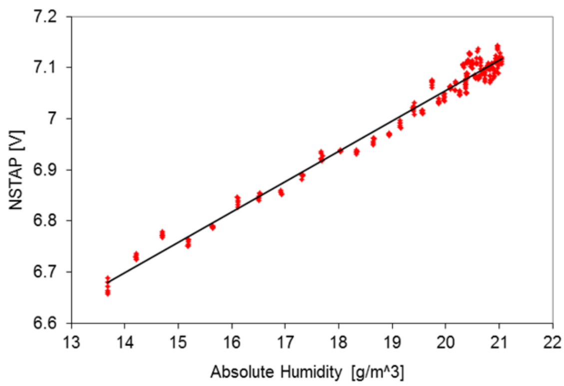

Figure 2. Preliminary results indicating the sensitivity to humidity of the new fast-response humidity sensor.

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