Application of Hot-Wire Anemometry in the High Subsonic Organic Vapor Flow Regime

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Abstract. Hot-wire anemometry (HWA) is a measurement technique which allows for the investigation of highly fluctuating flows. It has been widely used for turbulence studies including turbomachinery flow analysis, but relatively little is reported regarding its application in organic vapor flows. In this contribution, preliminary results are presented of an HWA study conducted in the test section of a closed-loop organic vapor wind tunnel using a constant-temperature-anemometry (CTA) system. The working fluid for this study was the perfluorinated ketone Novec™ 649, but air was also investigated for comparison reasons. Low subsonic up to high subsonic flows (i.e., up to $M = 0.7$) were considered, and the performance of HWA was assessed by obtaining turbulence intensities, velocity spectra, autocorrelation, and corresponding turbulent length scales. It was demonstrated that HWA is a useful tool for investigating turbulence phenomena in organic vapor flows although the dynamic loads and the wire Reynolds number levels are rather high.

Keywords: Experimental techniques · Hot-wire-anemometry · CTA · Turbulence · Organic vapor flows

1 Introduction and Scope of Research

The application of computational fluid dynamics (CFD) tools for the design and optimization of organic Rankine cycle (ORC) turbines has become a relevant topic in terms of sustainable power systems, and it is still growing (Colonna et al. 2015; Macchi and Astolfi 2017). However, there is a real need for experimental investigations and reliable flow measuring techniques in order to validate CFD methods for modelling and simulation of non-ideal gas flows.

The flow within a turbomachine is in general unsteady and turbulent. Hot-wire anemometry (HWA) is a measurement technique which allows for the investigation of highly fluctuating flow phenomena (Smolyakov and Tkachenko 1983), and it is still the primary tool in turbulence research, but relatively little is reported about its performance in organic vapor flows. So far, compressibility effects were investigated mainly under ideal gas conditions. HWA is a thermal measurement technique, based on the convective heat transfer between a heated thin cylinder (wire) and the relevant fluid (Bruun 1995). Because of the very fast thermal response of the thin wire, HWA allows

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for the investigation of highly fluctuating flow velocities. The scientific application of HWA has a long history. Although HWA is mostly used for obtaining velocities, it is from a physical point of view rather an area-averaged mass flow measurement. HWA is strongly affected by compressibility effects and fluctuations of thermodynamic quantities particularly in transonic flows (Kovasznay 1950; Morkovin 1956; Horstman and Rose 1977; Souza and Tavoularis 1999). Another well-known challenge arising in high-speed flow applications arises from the high dynamic wire loads, increasing the risk of wire breakage and short life time of the probes. Hence one might expect serious problems for HWA in organic vapor flows, because of the high density levels due to their high molecular complexities (although the low speed of sound might lead to somewhat moderate absolute flow velocities). A statement on the actual HWA breakage risk in organic vapor flows can only be given by means of experiments performed under realistic flow conditions. Apart from these issues, contamination and corrosion of the wire are also crucial because both can strongly disturb calibration efforts. Corrosion might be relevant because the hot-wire material is typically not stainless steel. Due to the fact that organic vapor test facilities and power systems are always characterized by a closed hermetic design, contamination with air dust should not be a serious issue.

Currently, there are only few operational wind tunnel test facilities available for investigating organic vapor flows. One of these test facilities is the closed-loop organic vapor wind tunnel (CLOWT), built up at Muenster University of Applied Sciences (Reinker et al. 2018; Reinker et al. 2019). Since CLOWT has been designed as a continuously running wind tunnel with the possibility to calibrate probes, it is a powerful tool for assessing the potential of HWA in the high subsonic flow regime. In this contribution, the outcome and the experiences are presented of a first preliminary experimental study conducted at CLOWT using a constant-temperature-anemometry (CTA) system.

2 Experimental Setup and Procedure

The considered CTA system was a modified system designed for higher wire temperatures with an overheat ratio of about $\tau \approx 2.3$ using a robust heated wire (diameter: d = 10 μm; length: L = 4 mm; material: gold-plated tungsten) provided by SVMtec GmbH, Stuttgart. Figure 1 shows the corresponding microscopic photograph and the dimensions of the CTA probe utilized in this study. The present experiments were performed in the calibration test section of the closed-loop organic vapor wind tunnel (CLOWT) using the perfluorinated ketone Novec™ 649 and dry air (see Fig. 2c). More details on the test facility CLOWT and its working principle can be found in previous publications (Reinker et al. 2018; Reinker et al. 2019).

After passing the centrifugal compressor, the working fluid was decelerated in the diffuser and entered the settling chamber where stagnation pressure p_0 (uncertainty $\Delta p/p$ = 0.7%) and total temperature T_0 (uncertainty $\Delta T/T$ = 0.18%) were measured. The mass flow rate m was measured by means of a mass flow device in the return of the wind tunnel (with maximum uncertainty level of $\Delta \dot{m}/\dot{m}$ = 1.6 – 4.5% depending on the actual operation conditions). Different turbulence intensities could be provided by means of variable screen sets, but during the present study, the settling chamber was not equipped with additional flow straighteners or screens in order to provide noticeable turbulence intensities (of order 0.5 up to 1.0%). In CLOWT, the flow is successively accelerated in a two-stage contraction zone. The first subsonic axisymmetric nozzle (from standard diameter DN500 to DN250) offers a moderate contraction ratio of about 3.7, whereas the second nozzle accelerates the flow to high subsonic or transonic flow, depending on the chosen modular nozzle device (see Fig. 2a). In the present study, the second contraction was achieved by a three-dimensional nozzle, based on additive manufacturing, providing a three-dimensional cross-section change from round to rectangular contraction (DN250 to 50 mm × 100 mm) leading to a total contraction ratio of about 38 (see Fig. 2c on the right). The probe blockage of 2% in the calibration test section was negligible in terms of disturbances on the static pressure p_1 which was measured at endwall pressure taps ahead of the hot wire (see Fig. 2b).

Actual vapor states and Mach numbers M in the test section were calculated using REFPROP data based on recorded pressures, temperatures, and mass flow rates and assuming isentropic nozzle flow. The heat transfer at the hot wire was driven by the temperature difference $T_w - T_f$ between hot wire and fluid. Special attention required the determination of the correct value of the wire temperature, T_w. For this purpose, the probe and electrical line resistances R_L were determined and then the wire temperature, T_w, which is a function of the temperature-resistance dependency of the wire material, was calculated. Details on this method can be found in (Bruun 1995). To calculate the fluid temperature T_f, which in fact was the recovery temperature, the recovery factor was assumed to $r = 0.89$, based on the Prandtl number of Novec™ 649. For signal processing a highspeed analog input module NI9229 of National Instruments (Delta-Sigma digitizer and analog prefiltering) was used with a sampling rate of 10 kHz and sampling duration of $t = 4$s. The relative uncertainty of the electrical bridge voltage $\Delta U_B/U_B$ was of order 1.5 up to 2.0%.

In a first set of experiments, a static calibration of the HWA system with Novec™ 649 as working fluid was performed at different densities (up to $\rho = 35$ kg/m^3), pressure levels (up to 3 bar), but at a fixed total temperature of about $T_0 = 95$ °C ± 0.5 °C. The mass flow rate was controlled by variation of the compressors running speed, n, leading to a Mach number range of about $M = 0.1$ up to 0.7. A laminar heat transfer correlation with coefficient functions A and B was assumed for the static calibration. In Eq. (1) U_B is the Wheatstone bridge voltage of the HWA, w is the ambient flow velocity, based on mass flow rate and cross-sectional area of the test section, d is the hot wire diameter, and μ is the viscosity.

$$\mathrm{Nu} = A(M,\tau) + B(M,\tau)\ \mathrm{Re}^{1/2} \quad \text{with} \quad \mathrm{Nu} \sim U_B^2/\left(T_w - T_f\right) \quad \text{and} \quad \mathrm{Re} = w\rho d/\mu \tag{1}$$

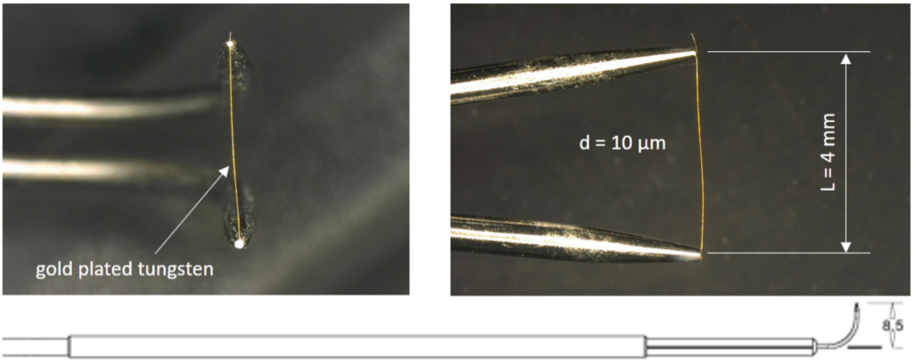

Fig. 1. Microscopic photograph and dimensions of the gold-plated tungsten hot-wire and the prongs.

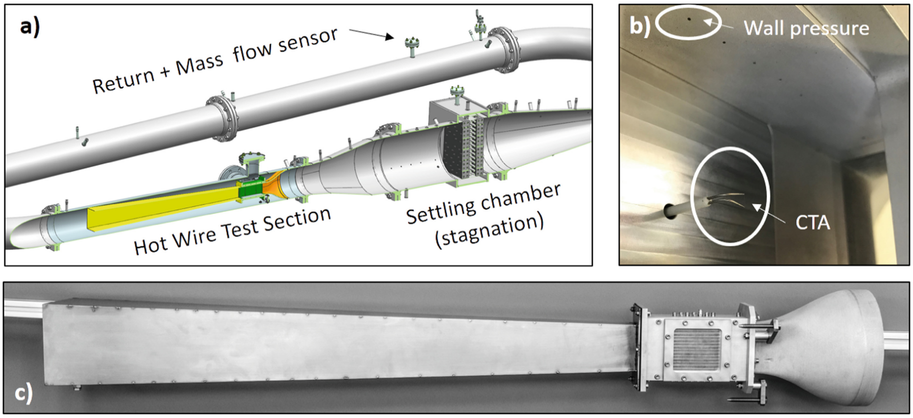

Fig. 2. a) CAD model of CLOWT with diffuser and settling chamber (stagnation conditions) on the right and hot wire test section on the left. b) Look into the test section including CTA mounting and wall pressure tap. c) Photograph of the modular high-speed test section including 3D-printed nozzle, rectangular modular test section, and diffuser (from right to left).

In a second step, the data from the calibration procedure was used to calculate the main flow velocities from the collected bridge voltage U_B. Using this velocity data set the turbulence intensity Tu was calculated by the relation $Tu = w'/\overline{w}$, with the root-mean-square of the turbulent velocity fluctuations w' and the mean velocity $\overline{w}$. Based on the assumption of isotropic turbulence, the formula considers only the main flow direction, which is obviously a simplification.

However, as an independent test of the turbulence level prediction, the classical turbulence sphere experiment, which is traditionally used for the characterization of low speed wind tunnels (Barlow et al. 1999), was conducted in the low speed test section (after the first contraction zone) at essentially incompressible flow conditions prior to the high-speed CTA measurements. Figure 3 shows on the left the polished turbulence sphere which was mounted in the centerline of the low speed test section. The corresponding drawing with global dimensions and positions of the pressure taps is shown on the right of Fig. 3. The stagnation pressure was measured at the leading edge and the base pressure at the aft surface, which was averaged by terms of four pressure taps. More details on the approved design of turbulence spheres and the corresponding calculation methods for the determination of *Tu* can be also found in (Barlow et al. 1999).

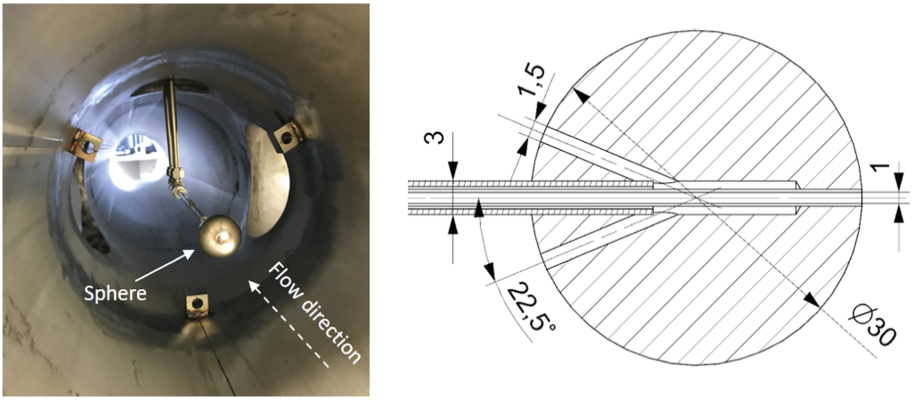

Fig. 3. Turbulence sphere in the basic test section (DN250) of the wind tunnel (left) and drawing of the turbulence sphere with all dimension (right). Front and rear pressure taps are equipped with separate pressure lines to measure the differential pressure.

3 Results and Discussion

The results of the static CTA calibration are shown in Fig. 4. It was found that the laminar heat transfer correlation (1) led to deviations less than 1.0%, and the typical deviation level was of only 0.3%. Inspection of Fig. 4 indicates that a systematic error trend was not obvious, but it should be noted that the highest deviation were observed at the highest Mach number (M = 0.7). Despite significant changes in density and other thermophysical material properties at other operating points, the laminar heat transfer correlation (1) still proofed its reliability.

The outcome of the turbulence investigations is shown in Fig. 5. On the left diagram, the results of CTA and turbulence sphere experiments conducted inside of the low speed test section under essentially incompressible flow conditions are shown. There was a good agreement observed between the CTA results and the independent turbulence sphere test. Interestingly, the flow control by the throttle valve in the return of the wind tunnel, see Fig. 2, led to higher turbulence intensities than the compressor running speed approach at fully opened valve. The effect of the second contraction on the turbulence intensity can be seen in Fig. 5 on the right. The turbulence intensity was reduced from its entry value of about 1.6% to a final level of about 0.5% after passing the second high-speed nozzle. It was observed that *Tu* increased systematically with increasing Mach number M to values of about Tu = 1.0% at M = 0.7.

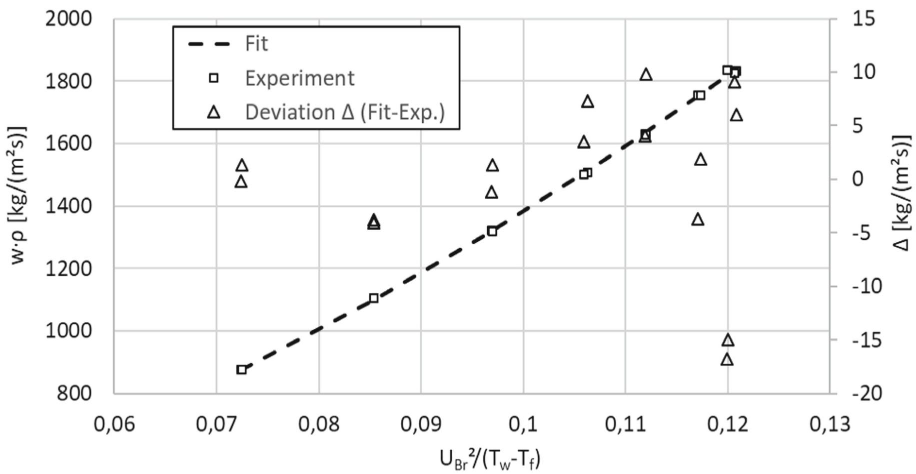

Fig. 4. Static calibration curve and deviations between fitting curve based on laminar heat transfer correlation (1) and experimental data obtained independently by mass flow sensor for subsonic organic vapor flow (Novec™ 649). The maximum error, which occurred at the highest Mach number of M = 0.7, was of order 0.9%.

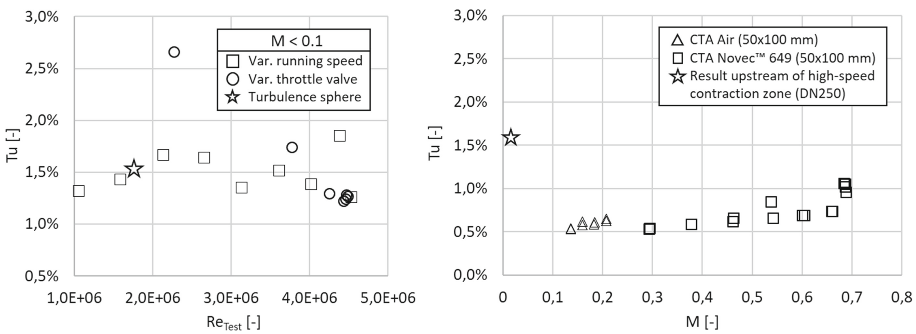

Fig. 5. Left: Turbulence intensities for Novec™ 649 in the low speed test section at different Reynolds numbers, measured by CTA and turbulence sphere. Right: Turbulence intensities, measured by CTA, for Air and Novec™ 649 in the high-speed test section downstream of the second contraction.

The spectral analysis of the CTA signals provided further insights into the turbulent flow behavior, but it exhibited also the impact of electrical noise due to the compressor drive and control unit. Figure 6 shows an example of such an un-filtered normalized power density spectrum (PSD) of the CTA signal U_B obtained at $M = 0.7$, corresponding to a compressor running speed of 3000 rpm (50 Hz).

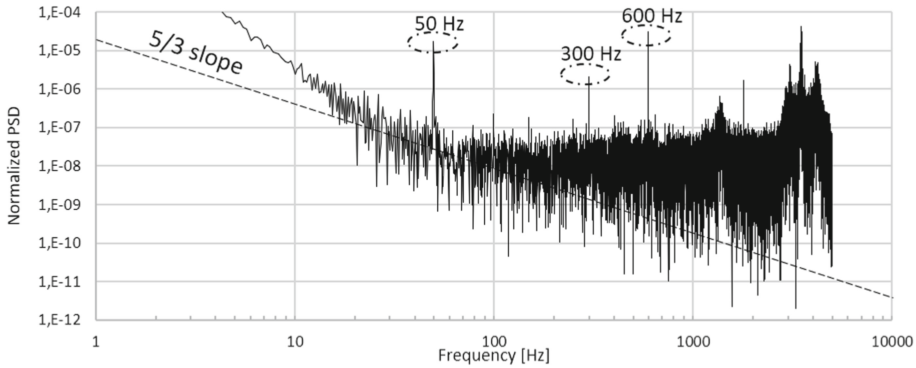

Fig. 6. Spectral analysis of an unfiltered (no cutoff filter) Hot-wire signal (Novec™ 649 at $\rho = 35$ kg/m^3 and M = 0.7) at 50 Hz compressor rotational speed. The rotor and blade passage frequencies are highlighted. The broken line corresponds to Kolmogorov's 5/3-law.

There are three regular or synchronous peaks observable in the power spectral density in Fig. 6, namely the rotational speed of the compressor at 50 Hz, the passage frequency of the six main compressor blades at 300 Hz, and the passage frequency of the twelve main and splitter blades at 600 Hz. The linear relation between compressor running speed n and peak frequencies was also observed for other rotational speeds much lower than 50 Hz (the effect shown in Fig. 6 was not caused by the European 50 Hz power grid and its harmonics, but is was related to the design of the compressor impeller). However, the high sensitivity of the employed CTA system was also demonstrated by the clear resolution of these synchronous peaks. Additional screens in the settling chamber would noticeably reduce these regular patterns, but for the present purpose, they served as benchmark.

The increasing deviation from Kolmogorov's 5/3-law at higher frequencies became obvious in Fig. 6, indicating the necessity to remove the impact of external electrical noise by terms of low-pass filtering of the CTA signal. The increase of the spectrum at higher frequencies was probably a result of the energy input from the un-shielded compressor control unit. Since the major contributions are covered by the lower frequency range, the exact choice of the filter limiting frequency was not essential for estimating the turbulence level Tu. Setting limiting frequency values of 1 kHz or 2 kHz led essentially to identical results regarding turbulence intensity and other turbulent quantities. For this reason, the 2 kHz lowpass filter was chosen for the investigations presented here.

The great potential of HWA for the investigation of turbulent compressible non-ideal gas flows was checked by obtaining the autocorrelation $f(r/\lambda)$ for air and Novec™ 649 at several Mach numbers (assuming the Taylor hypothesis). The autocorrelation f enables a determination of the turbulent micro length scale λ and the integral length scale Λ (Rotta 1972). The results for the present test section are shown in Fig. 7. The experimentally obtained autocorrelation agreed well with the theoretical models proposed by Loisianskii and Birkhoff for (incompressible) isotropic turbulence. This might be interpreted as a strong indication that the well-established turbulence models

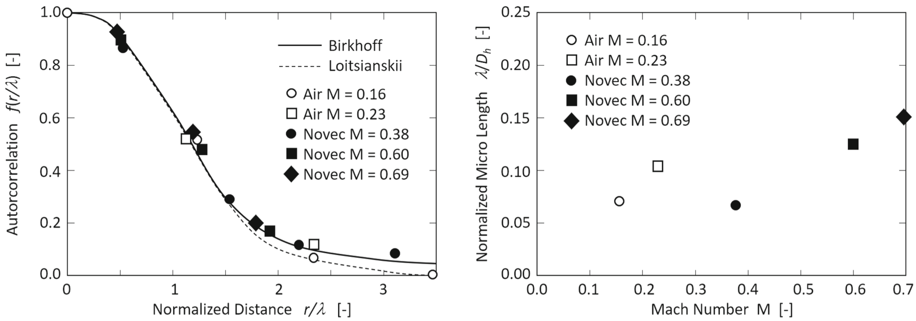

Fig. 7. Autocorrelation for Novec™ 649 and air at different Mach numbers (left) and turbulent micro length scale λ (normalized by means of the hydraulic diameter of the test section) against Mach number (right).

employed in CFD are also applicable for modelling high subsonic turbulent non-ideal gas flows. The turbulent micro length scale λ increased with Mach number M. Its value of $\lambda/D_h \approx 0.07$ (with D_h as the test sections hydraulic diameter) at very low Mach number, agreed well with observations for incompressible pipe and duct flows.

4 Conclusion and Outlook

The above experimental investigations demonstrated that hot-wire probes can withstand the considerable dynamic loads in high subsonic flows of heavy organic vapors at elevated density and temperature levels. This observation is generally promising for future experimental turbulence research dealing with non-ideal gas flows. Furthermore, the frequently employed laminar heat transfer correlation (1) proofed its reliability for high subsonic organic vapor flows, and static calibration of CTA in organic flows was conducted. The performance of the CTA system was assessed by obtaining turbulence levels in the wind tunnel and comparing the results with the outcome of an independent turbulence sphere test.

However, the hot-wire study presented here is far away from being completed and the authors recognized that hot-wire measurements can become extremely challenging in compressible organic vapor flow. Several relevant questions regarding signal processing and data reduction are still open. Furthermore, the design of hot-wire probes might be improved in order to provide higher spatial and temporal resolution.

The authors would be delighted if this first study could invite HWA experienced readers and experts to work on this interesting field. CLOWT has been intended to provide a test facility for collaborations, and the authors would highly appreciate such a collaboration with other researchers.

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References

Bruun, H.: Hot Wire Anemometry: Principles and Signal Analysis. Oxford University Press, Oxford (1995)

Barlow, J.B., Rae, W.H., Pope, A.: Low Speed Wind Tunnel Testing, 3rd edn. Wiley, New York (1999)

Horstman, C.C., Rose, W.C.: Hot wire anemometry in transonic flow. AIAA J. **15**, 395–401 (1977)

Colonna, P., Casati, E., Trapp, C., Mathijssen, T., Larjola, J., Turunen-Saaresti, T., Uusitalo, A.: Organic rankine cycle power systems: from the concept to current technology, applications, and an outlook to the future. ASME J. Eng. Gas Turbines Power **137**(10), 100801 (2015)

Kovasznay, L.S.G.: The hot-wire anemometer in supersonic flow. J. Aero. Sci. **17**(9), 565–572 (1950)

Macchi, E., Astolfi, M.: Organic Rankine Cycle (ORC) Power Systems. Elsevier, Amsterdam (2017)

Morkovin, M.V.: Fluctuations and hot-wire anemometry in compressible flows. Report North Atlantic Treaty Organization, Advisory Group for Aeronautical Research and Development (1956)

Reinker, F., Kenig, E.Y., aus der Wiesche, S.: Closed loop organic vapor wind tunnel CLOWT: commissioning and operational experience. In: Proceeding ORC 2019 Athens, Greece, paper-ID 47 (2019)

Reinker, F., Kenig, E.Y., aus der Wiesche, S.: CLOWT: a multifunctional test facility for the investigation of organic vapor flows. In: Proceedings ASME 2018 5th Joint US-European Fluids Engineering Division Summer Meeting, Montreal, Canada (V002T14A004) (2018)

Rotta, J.C.: Turbulente Strömungen. Teubner, Stuttgart (1972)

Smolyakov, A.V., Tkachenko, V.M.: The Measurement of Turbulent Fluctuations. Springer, Berlin (1983)

De Souza, F., Tavoularis, S.: Hot-wire response in high-subsonic flow, conference paper AIAA-99–0310 (1999)