SHOCK LOSSES AND PITOT TUBE MEASUREMENTS IN NON-IDEAL SUPERSONIC AND SUBSONIC FLOWS OF ORGANIC VAPORS

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ABSTRACT

The present work documents extensive experimental campaigns involving the first ever L-shaped Pitot tube measurements in non-ideal subsonic and supersonic flows of siloxane MM vapor, a fluid commonly employed in high-temperature ORCs. Testing was carried out on the Test-Rig for Organic Vapors (*TROVA*) at Politecnico di Milano, a blow-down wind tunnel specifically designed to reproduce non-ideal flows of organic vapours in conditions representative of ORC turbines operation.

A pneumatic lines scheme involving nitrogen flushing was purposely implemented to allow probes insertion in the plant test section whilst minimizing response time. Pitot tubes testing in subsonic flows at Mach number 0.2 and 0.5 was first carried out to complete the pneumatic system commissioning and evaluate its performance for kinetic head, total and static pressure measurements against direct reference counterparts from the *TROVA* plant. This also allowed to experimentally verify that flow non-ideality does not affect the behaviour of a Pitot tube, indicating that no particular calibration is required for this type of instrument in such subsonic conditions. Finally, Pitot tubes were employed to perform the first ever direct total pressure loss measurement across normal shock waves in non-ideal flows of siloxane MM vapors.

The work here reported establishes reliable methodologies for Pitot tubes testing in non-ideal subsonic and supersonic flows relevant to the ORC world, paving the way towards blade cascade testing and pressure probes use in research and industrial contexts where non-ideality is relevant.

1 INTRODUCTION

Detailed experimental data characterizing non-ideal flows for Organic Rankine Cycle (*ORC)* applications is currently not widely available in the open literature due to the intrinsic difficulties in running dedicated experimental facilities. Most high-temperature ORC working fluids are liquids at standard room temperature and pressure, such as siloxanes and some complex hydrocarbons. Typical inlet turbine flows are instead at saturated, superheated or supercritical conditions, with temperatures and pressures ranging from about 100 to 400 °C and 10 to 50 bar (Macchi and Astolfi, 2016). Thus, to reproduce realistic conditions in a wind tunnel, a closed gas cycle or a phase transition thermodynamic cycle must be put in place. These are noticeably more complicated and expensive with respect to operation with incondensable gases such as air, where compressed air storage tanks or continuous loops are often sufficient to carry out an experimental campaign. Measurement procedures are also more complex due to the high fluid temperature involved and condensation issues in pneumatic lines. Moreover, the non-ideal flow field dependance on stagnation conditions significantly increases the number of flows to be experimentally reproduced for a complete characterization.

Despite these difficulties, several active plants are starting to provide valuable experimental data on relatively simple yet extremely useful geometries such as converging-diverging nozzles. These allow to reproduce elementary flows important for fundamental fluid dynamics studies and are also the simplest geometry representative of blade passages in ORC turbines. Amongst these so-called *nozzle-fitted facilities* is the *Test Rig for Organic VApors* (*TROVA*) (Spinelli et al., 2013) at the Laboratory of Compressible Fluid-dynamics for Renewable Energy Applications (CREA Lab) of Politecnico di Milano, where all the experimental campaigns concerning the present work were carried out. Other plants of this kind are the ORCHID (Head et al., 2016) at TU Delft, the CLOWT (Reinker et al., 2017) at Muenster University of Applied Sciences and the dense-gas blowdown facility at Imperial College London (Robertson et al., 2020). Several turbine-fitted facilities mainly devoted to performance measurement of the different components and of the overall thermodynamic cycle also exist, such as the *LUT micro-ORC test rig* at Lappeenranta – Lahti University of Technology (Turunen-Saaresti et al., 2017). The ORCHID at TU Delft is designed to also operate with a turbine instead of a nozzle.

Due to the peculiarities of non-ideal vapor flows in *ORCs*, measurements such as velocity magnitude and direction, mass flow rate or turbine performance, which are routinely carried out in more standard cycles and turbomachinery (e.g. gas turbines operating with air and combustion gases), are not possible yet with available technologies. One of the main issues in real operating plants is indeed the closure of mass and energy balances due to the lack of reliable mass flow rate measurements (Zanellato et al., 2017). Even blade cascade testing, quite common in the design process of gas and steam turbines, is only starting to take place for such flows. To the authors' knowledge, the first experimental campaign of this kind was very recently carried out at Whittle Laboratories of Cambridge University in a newly modified transient wind tunnel of Ludwieg tube-type, where annular turbine cascade flows of R134a were characterized with static pressure measurements (Baumgärtner et al., 2019). Upon further upgrade of the test rig, wake measurements of R134a flows in the same cascade were performed with a wedge probe with substantial complementary use of CFD calculation (Baumgärtner et al., 2020).

One of the main reasons for the difficulties in real ORC plant measurements and in blade cascade testing is that no appropriately calibrated instrumentation for non-ideal conditions is currently available. Indeed, none of the previously mentioned wind tunnels for non-ideal flows is mature enough to be routinely employed as a dedicated calibration facility for pressure probes. Research efforts are now starting to move towards this direction. The first published works on the topic are from the *CLOWT* plant at Muenster University of Applied Sciences. Results on the performance of a rotatable cylinder Pitot probe in high subsonic flows with fluid NovecTM 649 were recently presented (Reinker et al., 2020) as part of a preliminary study to establish measurement techniques for the determination of Mach numbers in high-subsonic and transonic organic vapor flow fields.

The research effort documented in this paper represents a contribution to the development and use of measurement systems for pressure probes operating with non-ideal flows of interest in the ORC field. L-shaped Pitot-type probes were employed for pneumatic system commissioning and with a view of allowing immediate transposition in industrial applications. For this reason, they were preferred to the more complex directional pressure probes usually involved in more research-oriented studies. Moreover, Pitot tubes are a necessary intermediate step towards the calibration of directional probes for non-ideal flows and were therefore purposely chosen as the starting point for further developments in the field.

Subsonic testing was carried out on the *TROVA* with siloxane MM (hexamethyldisiloxane, $\mathrm{C_6H_{18}OSi_2}$) in conditions representative of measurement sections in real *ORC* plants where Pitot-tubes can be employed for mass flow rate and performance measurement. Supersonic testing was also carried out to measure directly, for the first time ever, total pressure losses across shocks of non-ideal flows of MM vapor, setting the foundations for future testing of blade cascades operating with such flows.

The paper is structured as follows. Section 2 describes the working principles of the *TROVA* experimental facility, its components and instrumentation. Section 3 details the pneumatic system implemented for pressure probe measurements in the *TROVA*. Section 4 reports experimental results of subsonic Pitot tube measurements and Section 5 documents direct total pressure loss measurement across shocks in non-ideal flows of siloxane MM.

2 EXPERIMENTAL SETUP

2.1 Test Rig for Organic Vapors - TROVA

The Test Rig for Organic VApors (*TROVA*) is a blowdown wind tunnel built with the aim of characterizing non-ideal flows of organic vapors representative of turbine expansions in ORCs. Experiments are carried out with fluid siloxane MM (hexamethyldisiloxane, $\mathrm{C_6H_{18}OSi_2}$), commonly employed in medium/high temperature *ORCs*. The working fluid is isochorically heated in a High-Pressure Vessel (*HPV*) until desired temperature and pressure are reached. It is then discharged to a Low-Pressure Vessel (*LPV*) by passing through a settling chamber (plenum) and expanding in the test section through a purposely designed planar nozzle.

TROVA operation is intrinsically transient due to its batch nature. Before the beginning of a test, the test section and *LPV* are vacuumized to MM saturation pressure at room temperature ($P \sim 50\ \mathrm{mbar}$). After test start, a peak is reached and then pressure decreases in time with a low frequency content ($\sim 1\ \mathrm{Hz}$) related to the emptying of the *HPV*. Due to the decreasing pressure linked to the plant batch nature, the most non-ideal flow conditions are achieved at the beginning of each test.

More detail on *TROVA* design and operation can be found in Spinelli et al. (2013).

2.2 Nozzle Expansion Characterization and Instrumentation

Flow expansions are characterized by total conditions measurements in the plenum upstream of the test section, where velocity is low enough (about $1\ \mathrm{m/s}$) for kinetic energy to be negligible. Thus, total pressure P_T is measured at a wall tap with an absolute pressure transducer and total temperature T_T with thermocouples. Total temperature and pressure can vary in the range $200 - 260\ ^\circ\mathrm{C}$ and $7 - 24\ \mathrm{bar}$ respectively for fluid MM.

Nozzle flow is characterized by static pressure measurements at wall taps of $0.3\ \mathrm{mm}$ in diameter machined on the rear plate of the test section along the nozzle axis. Absolute piezoresistive transducers are flush-mounted and are directly exposed to high temperature organic vapor flows. Due to their intrinsic temperature sensitivity, transducers must be calibrated both in pressure and temperature from vacuum to full scale ($3.5 \leq FS \leq 40\ \mathrm{bar}$) and in the range $25 - 300\ ^\circ\mathrm{C}$. Thermocouples are calibrated in the same temperature range. The expanded uncertainty is $0.07\ \%$ of the full scale for pressure sensors and about $1°C$ for thermocouples. Discrete pressure measurements in supersonic conditions were supported by schlieren visualizations. Details on the optical apparatus can be found in Spinelli et al. (2018).

The total-static Pitot tube shown in **Figure 1** with a stem length of $25\ \mathrm{mm}$, outer diameter of $1.59\ \mathrm{mm}$ and six taps on the static ring was employed in subsonic testing. The simple Pitot tube (a total pressure probe) in **Figure 2** with a stem length of $35\ \mathrm{mm}$ and outer diameter of $1.6\ \mathrm{mm}$ was instead used for shock loss measurements in supersonic flow. Both probes feature a total pressure tap diameter of $0.6\ \mathrm{mm}$.

Figure 1: Total-static Pitot tube employed in subsonic testing.

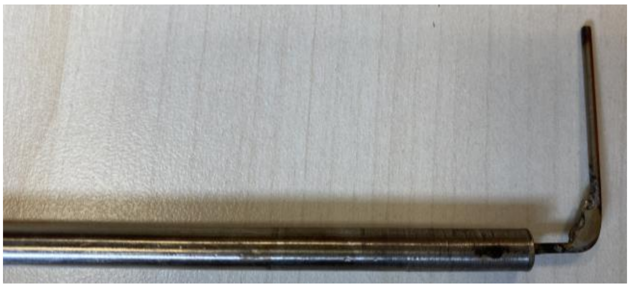

Figure 2: Simple Pitot tube (total pressure probe) used for shock loss measurements in supersonic flow.

2.3 Nozzles

Planar choked converging nozzles are used in the present work as a subsonic wind tunnel for Pitot tubes in non-ideal flows. They are characterized by a portion with constant cross-sectional area yielding design Mach numbers of 0.2 and 0.5, and are named accordingly as *cMM02* and *cMM05* as illustrated in **Figure 3**. The first convergent section is determined by a 5^{th} order polynomial, yielding a double concavity that provides gentle flow acceleration up to the defined Mach number and reduces flow non-uniformity. This portion and the constant cross-section one (semi-height $h = 19$ mm) are the same for both nozzles. The second convergent is a straight line that ends at the throat, which is always choked due to the very low pressure in the *LPV*. The slope is the same for both *cMM02* and *cMM05*, but the length is such that the area ratio between throat and constant cross-section corresponds to the desired Mach number at design total conditions $P_T = 5$ bar and $T_T = 210$ °C.

This nozzle design allows the evaluation of static pressure Pitot tube measurements by direct comparison of pressure at the end of the line connected to the probe static ring to transducers mounted on adjacent pressure taps. Indeed, compared measurement points are all located in the constant cross-section portion of the nozzle, so the same pressure should be found. A front view of the test section with nozzle *cMM02* and inserted total-static Pitot tube is reported in **Figure 5.**

Planar converging-diverging nozzle *nW-M15* in **Figure 4** was instead employed for supersonic Pitot tubes testing at Mach number $M{\sim}1.5$. The convergent part was designed according to the same procedure used for subsonic nozzles. The diverging portion shape was determined through the *method of characteristics* (*MOC*), implemented according to Zucrow and Hoffman (1977), coupled with a suitable thermodynamic model for non-ideal gases (see Guardone et al. (2013)) to deliver a uniform Mach number and a velocity parallel to the nozzle axis at the exit section. A front view of the test section with nozzle *nW-M15* and inserted total pressure probe can be found in **Figure 6**.

For all nozzles, depth is imposed by the test section to 18.7 mm.

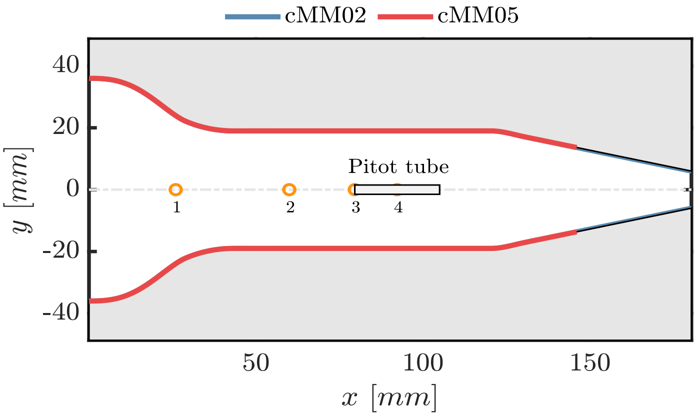

Figure 3: Planar choked subsonic nozzles *cMM02* and *cMM05*. Pressure taps and Pitot tube are also shown.

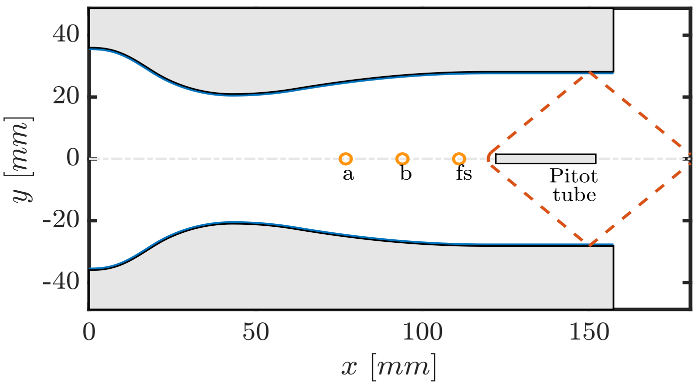

Figure 4: Planar converging-diverging nozzle *nW-M15*. Pressure taps, Pitot tube and expected bow shock are also shown.

Figure 5: Front view of the test section with planar choked nozzle *cMM02* and inserted total-static Pitot tube.

Figure 6: Front view of the test section with planar converging-diverging nozzle *nW-M15* and inserted total pressure probe.

3 PNEUMATIC LINES

When probes are employed, differential pressure measurements are carried out between the various probe taps or between a probe tap and the respective plant reference quantity in order to minimize the final measurement uncertainty. This requires the use of pneumatic lines.

Since siloxane MM is liquid at room temperature and considered operating pressures during tests, unheated pneumatic lines are subject to condensation. This can lead to poor measurements quality related to presence of vapor-liquid menisci, hydrostatic head, and time delay due to mass-sink effects.

A pneumatic lines scheme involving nitrogen flushing was purposely implemented to allow probes insertion in the plant test section whilst avoiding the above issues. As illustrated in **Figure 7**, the system is directly connected to nitrogen storage tanks and pressure is regulated through a pressure reducer to just above the maximum expected one during the test. Electro valves are actuated by a *Labview®* program to open as the test is triggered and close right after the pressure peak is reached in the test section. This ensures that each line only contains nitrogen at all times during a test and no MM vapor enters it, so as to avoid condensation. As the test proceeds, nitrogen exits the line through the static tap into the test section as line pressure is in equilibrium with the decreasing test section one. Particular care was taken during system design and components positioning to minimize lines length and fittings volume, so as to decrease the overall response time as much as possible.

The complete pneumatic lines configuration for subsonic probes testing here presented is specifically devised so that each quantity measured by the probe can be compared against plant references, allowing to evaluate the system behavior. The quantities of interest to be measured during *TROVA* testing of Pitot tubes in subsonic flows of Siloxane MM are:

- $P_{t,ref}$: reference total pressure in the plenum, measured with a flush mounted absolute transducer;
- $P_{s,ref}$: reference static pressure in the constant cross section part of the subsonic choked nozzle, measured with a flush mounted absolute transducer at tap number 2 in **Figure 3**;
- $P_{t,line}$: total pressure measured in the line exiting a pressure tap in the plenum;
- $P_{s,line}$: static pressure measured in the line exiting the wall tap in the constant cross-section region of the nozzle at tap number 4 in **Figure 3**, in correspondence of the Pitot tube static ring;
- $P_{t,pitot}$: total pressure measured in the line connected to the total pressure port of the Pitot tube;
- $P_{s,pitot}$: static pressure measured in the line connected to the static ring of the Pitot tube;
- $\Delta P_{ts,line}$: reference kinetic head directly measured with a differential transducer between the total pressure tap in the plenum and static wall tap number 4 in **Figure 3***;*
- ΔP_t: total pressure difference directly measured with a differential transducer between the pressure tap in the plenum and the Pitot tube one;

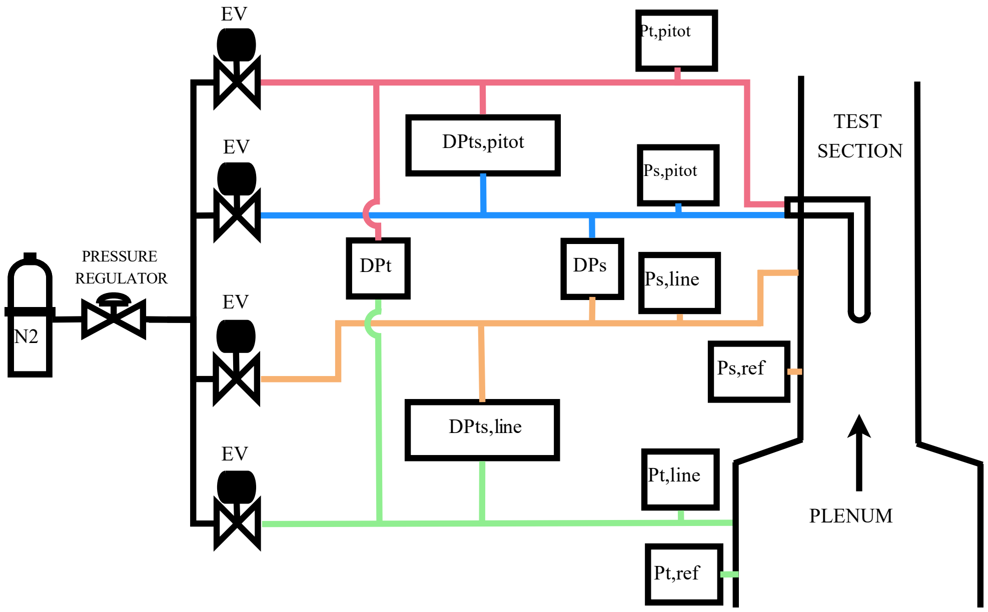

Figure 7: Flushed pneumatic lines scheme for Pitot tube testing in subsonic flows of Siloxane MM. Rectangular boxes represent pressure transducers.

- ΔP_s: static pressure difference directly measured with a differential transducer between static wall tap number 4 and the Pitot tube one;
- $\Delta P_{ts,pitot}$: kinetic head directly measured with a differential transducer by the Pitot tube.

The last four quantities are acquired in differential mode to minimize measurement uncertainty, as previously mentioned. Absolute transducers on each line are used as support to pinpoint any possible measurement issues.

The pneumatic system for measurements in supersonic conditions is simpler. Compared to the complete subsonic configuration, only the difference ΔP_t between the plenum total pressure (upstream of the shock) and the probe total pressure (downstream of the shock) is of interest here. Quantity ΔP_t is now a direct measure of the total pressure loss across the shock. Absolute transducers are still present on each line to help with possible issues identification.

Employed differential transducers are from the *Schaevitz P2100* and *Kulite XTL-3-375(M)* series, with full scale chosen in the range $0.7 - 5.9$ bar (uncertainty range $1.7 - 3.3$ ‰ of the full scale) according to the expected measured pressure difference.

4 PITOT TUBE MEASUREMENTS IN NON-IDEAL SUBSONIC FLOWS

Pitot tubes testing in non-ideal subsonic MM flows involved about 30 runs with *cMM02* and *cMM05* at initial total conditions $P_T \cong 7.4$ bar, $T_T = 202 - 210$ °C (compressibility factor at total conditions $Z_T \sim 0.8$). Repeated testing showed good consistency and reliability of results. For brevity, only data from one exemplary run at nominal Mach number $M = 0.5$ is reported in **Figure 8** to **Figure 11**.

All acquired absolute pressures are plotted as a function of time in **Figure 8**. The reference total pressure $P_{t,ref}$ measured with a flush-mounted transducer is superposed to $P_{t,line}$ and $P_{t,pitot}$. The total pressure difference ΔP_t, directly measured with a differential transducer, is never larger than $7\ mbar$. This is evident in **Figure 10**, where ΔP_t is reported together with pressure computed from absolute transducers. All three quantities agree, although the calculated pressure differences have a very large error-bar due to the large uncertainty propagated from absolute measurements. This highlights the importance of using differential transducers instead of absolute ones in the present case.

Quite analogously, the three measured static pressures $P_{s,ref}$, $P_{s,line}$ and $P_{s,pitot}$ in **Figure 8** are also superposed. Consistently, the static pressure difference ΔP_s in **Figure 11** is always well below 3 mbar and its trend agrees very well with the difference between absolute transducers. Given the good measurement performance in both total and static quantities, the kinetic head reported in **Figure 9** shows a perfect overlap between readings from all differential and absolute transducers.

In percentage terms with respect to the kinetic head, differences between Pitot tube and *TROVA* reference quantities are always below 3 % for total pressure and 1.5 % for static pressure for all Mach numbers. These values are fairly constant during all tests and in line with findings from a preliminary characterization in air (not reported here for brevity), indicating an adequate performance of the complete pneumatic system in non-ideal subsonic flows of siloxane MM for total, static and kinetic head measurements.

Since Pitot tube performance variation during tests is relatively limited, it can be concluded that the level of flow ideality does not significantly affect its behavior. Thus, no particular calibration is required for Pitot tubes in non-ideal flows, but the instrument total, static pressure and/or kinetic head readings can be simply coupled with a total temperature measurement and a suitable thermodynamic model to calculate isentropic expansions in order to determine flow quantities, including local velocity, density and Mach number. This provides useful information for direct Pitot tubes use in engineering processes involving non-ideal flows.

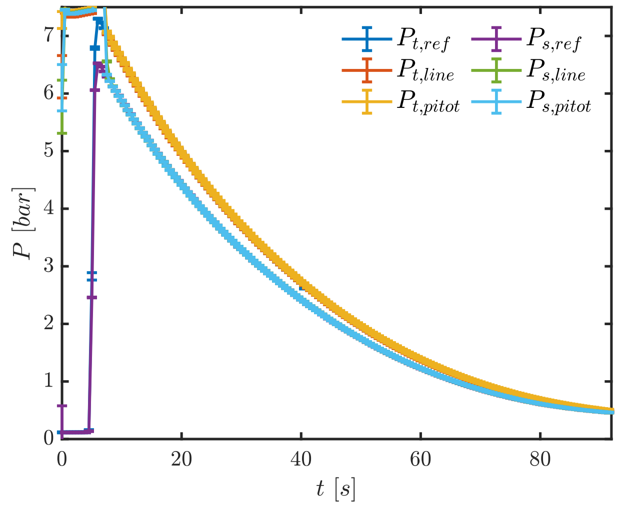

Figure 8: Absolute pressures measured during Pitot tube testing in subsonic conditions.

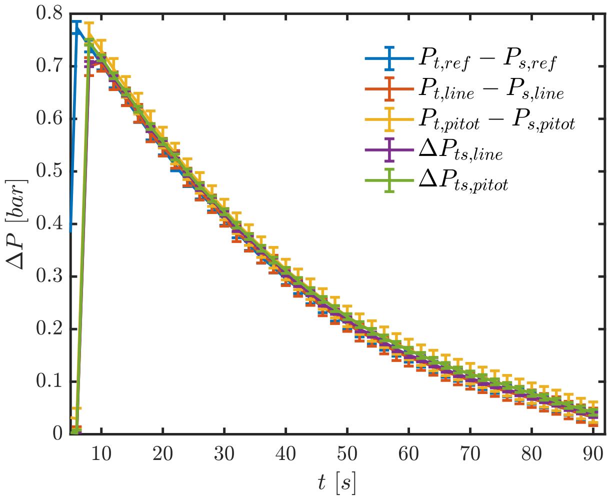

Figure 9: Kinetic head during Pitot tube testing in subsonic conditions.

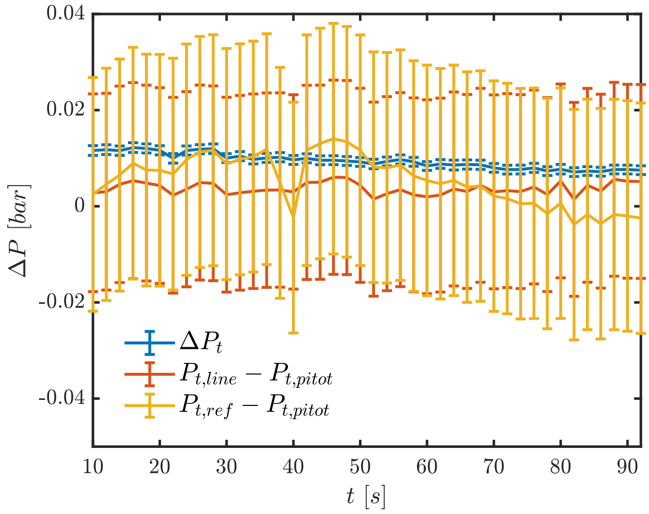

Figure 10: Total pressure difference during Pitot tube testing in subsonic conditions.

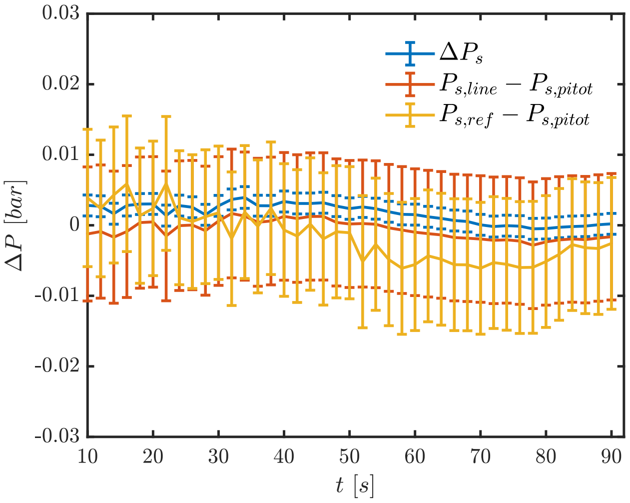

Figure 11: Static pressure difference during Pitot tube testing in subsonic conditions.

5 SHOCK LOSS MEASUREMENTS IN NON-IDEAL SUPERSONIC FLOWS

The first ever direct total pressure loss measurements across normal shocks in non-ideal flows of siloxane MM vapor are here reported. Initial total conditions of $P_T = 12.76$ bar and $T_T = 233$ °C were considered ($Z_T = 0.66$) for the present experimental campaign. Data consistency was verified by test repetition, and results from one exemplary run are reported here only.

The schlieren image of the nozzle divergent in **Figure 12** shows that the wind tunnel operating regime is the expected one, with supersonic flow impinging on the probe tip resulting in a bow shock that is locally normal to it.

Figure 13 reports all measured pressures during the test, labelled according to pressure taps in **Figure 4** and to the pneumatic system scheme in **Figure 7**. Pressure $P_{t,line}$ is in perfect agreement with the reference total pressure in the plenum $P_{t,ref}$ after line flushing has ended, indicating no issues on the upstream total pressure line to the differential transducer. The two pressures are within error bars of one another from test time $t = 7\ s$, so less than $0.4\ s$ after peak pressure was reached.

The absolute total pressure measured by the Pitot tube $P_{t2,pitot}$ is compared to the theoretical post-shock total pressure $P_{t2} - nIG\ P_{fs,exp}$ calculated from the experimental free-stream pressure P_{fs}, measured at the last tap positioned just before the probe, assuming a normal shock at the probe tip and by numerically solving conservation equations across the shock coupled with the Helmoltz energy-based fundamental relation of Span-Wagner type embedded in the *FluidProp* library (Colonna et al., 2004). The agreement is quite satisfactory considering that discrepancies are always below 2 % with respect to the measured post-shock total pressure $P_{t2,pitot}$.

Figure 13 also reports total pressure loss across the shock ΔP_t directly measured with the differential transducer, together with the total pressure difference $\Delta P_t - nIG\ P_{fs,exp}$ calculated consistently with $P_{t2} - nIG\ P_{fs,exp}$ above. The latter pressure drop is always lower than the experimental value. At $t = 10$ s the difference between the two is 200 mbar, decreasing to 75 mbar at $t = 25$ s and to 20 mbar at $t = 50$ s. Whilst these are not negligible discrepancies in absolute terms, they are a satisfactory result in percentage terms, with differences that are only 3 % of the pre-shock kinetic head at test start, down to 1 % at the end of the test.

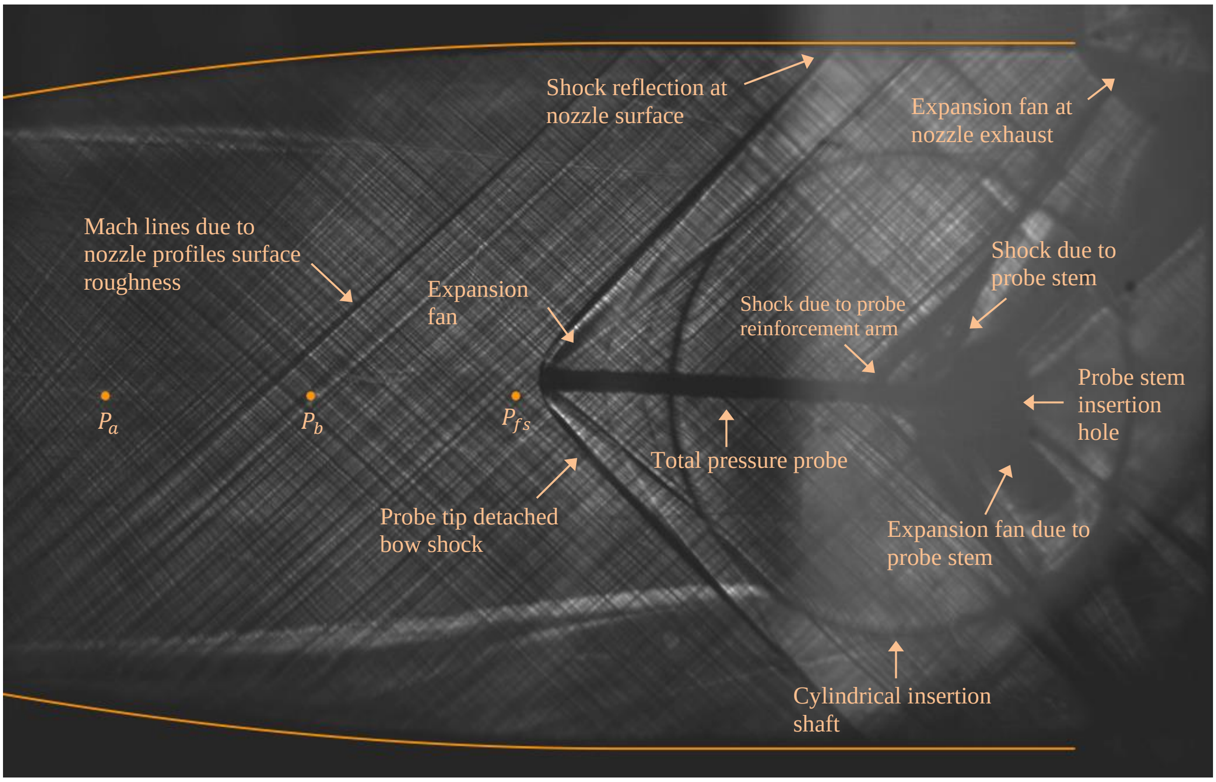

Figure 12: Schlieren image from an exemplary TROVA test for direct total pressure loss measurements across normal shocks in non-ideal flows of siloxane MM vapors. Nozzle contour, pressure taps and main flow features are highlighted.

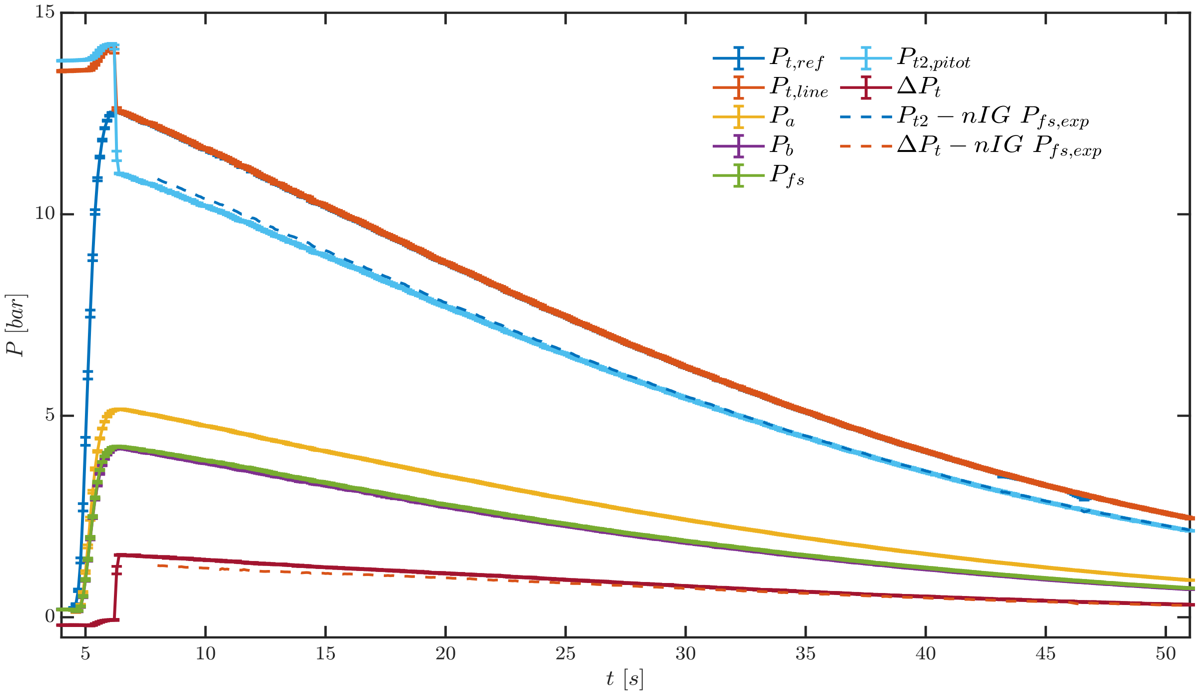

Figure 13: Pressures during an exemplary TROVA test for direct total pressure loss measurements across normal shocks in non-ideal flows of siloxane MM vapors.

The differences between measured shock losses and those calculated from free-stream pressure are attributed to a possible shock-boundary layer interaction at the wall, resulting in a measured P_{fs} at the wall which is larger than the one actually experienced by the probe tip at nozzle axis. As a consequence, the probe free-stream Mach number is larger than the one corresponding to the measured P_{fs}, consistently with the fact that measured shock losses are larger than calculated ones.

6 CONCLUSIONS

The present work reports results from extensive experimental campaigns involving the first ever L-shaped Pitot tube measurements in non-ideal subsonic and supersonic flows of siloxane MM vapor.
A pneumatic lines scheme involving nitrogen flushing was purposely implemented to allow probes insertion in the test section of the *Test Rig for Organic VApors* blow-down wind tunnel at Politecnico di Milano whilst avoiding issues linked to possible condensation.
Pitot tube testing in subsonic flows at Mach numbers 0.2 and 0.5 allowed to verify the adequate performance of the complete pneumatic system in non-ideal subsonic flows of siloxane MM for total, static and kinetic head measurements. Moreover, Pitot tube behaviour was found not to be affected by the level of flow non-ideality, indicating that no calibration is required for this type of instrument in such subsonic conditions.
Finally, a simple Pitot tube (a total pressure probe) was employed to perform the first ever direct total pressure loss measurement across normal shock waves in non-ideal flows of siloxane MM vapors. Results were found to be in good agreement with theoretical shock losses predicted from the solution of conservation equations, setting the foundations for future directional pressure probe calibration and testing of blade cascades operating with such flows.

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